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BUILDING STONES: THEIR PROPERTIES,
DECAY, AND PRESERVATION

BUILDING STONES

THEIR PROPERTIES, DECAY, AND
PRESERVATION

BY

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To
MY ESTEEMED FRIEND
T. STAINFORTH, B.A., B.Sc.

PREFACE

THE chief object in writing this book is to supply an introduction to one of the most difficult subjects concerned with the architectural profession and the building industry, and one which has been sadly neglected. It is not a complete account of all the building stones, nor does it pretend to have exhaustively dealt with the subjects of decay and preservation, for to do all this would require considerably more space than the author has had allowed to him for a first edition. As the most used stones for exteriors are the limestones and sandstones, these have been given preference, the marbles and granites receiving just a brief notice. Some of the stones described in the text are not now quarried, but it was considered necessary to include them, as they are in buildings of importance, and are in some instances suffering from intense decay.

Every endeavour has been made to deal with the scientific portions of this work in a manner understandable by those not acquainted with advanced chemistry, physics, and geology. It has not been an easy task, and it is to be hoped that the attempt has at least approached the borderline of success.

Whatever the shortcomings of this work, and it is felt that there are many, it may prove of some slight assistance in solving some of the difficult problems which beset those whose work brings them among the building stones.

Many thanks are due to Mr. B. Cook for preparing the photomicrographs from sections of the building stones, and to Mr. Stanley C. Wood for taking all the other photographs used to illustrate this work.

To his esteemed friend Mr. H. Garnett the author tenders his best thanks for the care bestowed in preparing the many slides used for microscopic examination, and for the preparation of the photomicrographs, and to his technical assistant, Mr. S. Geard, acknowledgments are made for many kind and helpful suggestions.

A very valued friend and adviser, who wishes to remain unnamed, must not be forgotten, for to him the author owes a debt of gratitude for much good advice.

For much help in collecting data in the field and for the preparation of the whole of the typescript the author tenders his best expressions of appreciation to his secretary, Miss R. M. Stancombe.

To his wife, who has given much assistance and who has prepared the greater portion of the index, the author offers his best thanks.

ARTHUR R. WARNES,

RICHMOND, SURREY,
1926.

CONTENTS

PREFACE	PAGES
- - - - -	vii

CHAPTER I

THE GEOLOGY OF BUILDING STONES—NEED OF FIELD WORK— STRUCTURAL CHARACTERS OF ROCKS—IGNEOUS ROCKS— SEDIMENTARY ROCKS—MECHANICALLY FORMED ROCKS— ORGANICALLY FORMED ROCKS—CHEMICALLY AND BIO- LOGICALLY FORMED ROCKS—CLASSIFICATION OF STRATA— CHIEF MINERALS OCCURRING IN ROCKS—BIBLIOGRAPHY	17-33
---	-------

CHAPTER II

BUILDING STONES: ANCASTER STONE—ANSTON STONE—ASPATRIA STONE—THE BATH STONES—BEER STONE—BLAXTER STONE —BOLSOVER MOOR STONE—BRAMLEY FALL STONE—BLUE BRISTOL PENNANT STONE—CAEN STONE—CAITHNESS STONE— CHILMARK STONE—CLIPSHAM STONE—CLOSEBURN STONE— CLUNCH STONE—COTSWOLD DALE STONE—CORSEHILL STONE —CRAIGLEITH STONE—DARLEY DALE STONE—DOULTING STONE—FOREST-OF-DEAN STONES—GATTON STONE—GIFNOCK LIVER ROCK STONE—HAILES STONES—HAM HILL STONES— HEADINGTON STONE—HOLLINGTON STONES—HOPTON WOOD STONE—HOWLEY PARK STONE—HUDDLESTONE STONE— KENTON STONE—KENTISH RAG STONE—KETTON STONES— LECKHAMPTON STONE—MANSFIELD WOODHOUSE STONE— MANSFIELD STONES—MINCHINHAMPTON STONE—PAINSWICK STONE—PARK SPRING STONE—PARK NOOK STONE—PENNANT STONE—PORTLAND STONE—PRUDHAM STONE—PURBECK STONE—QUARELLA STONES—RED WILDERNESS STONE— ROBIN HOOD STONE—ROCHE ABBEY STONE—ST. BEES STONES —STORETON STONE—WEALDEN STONE—WELDON STONE	34-108
---	--------

CHAPTER III

BUILDING STONES (<i>continued</i>): MARBLES—BRITISH MARBLES— ASHBURTON — IPPLEPEN — PURBECK — HOPTON WOOD — OGWELL—PETITOR—IONA—IRISH MARBLES—CONNEMARA GREEN—IRISH BLACK—FRENCH MARBLES—CAMPAN VERT— CAMPAN ROSE—CAMPAN MELANGE—LANGUEDOC—JAUNE
--

CHAPTER III (*Continued*)

	PAGES
LAMARTINE — BELGIAN MARBLES — ST. ANNE — BELGIAN BLACK — ROUGE MARBLES — BLUE BELGE — PORTUGUESE MARBLES — EMPEROR'S RED — VIDRACO MARBLES — NORWE- GIAN MARBLES — GREEK MARBLES — SWEDISH MARBLES — SWISS MARBLES — ITALIAN MARBLES - -	109-118

CHAPTER IV

BUILDING STONES (<i>continued</i>): GRANITES — CHEESEWRING — COLCERROW — CORRENIE — CREETOWN — DALBEATTIE — DANCING CAIRNS — DE LANK — DYCE — KEMNAY — LAMORNA — MOUNTSORREL — PENRYN — PETERHEAD — PRINCETOWN — ROSS-OF-MULL — RUBISLAW — SCLATTIE — SHAP — TOR — TYRE- BEGGAR - - - - -	119-127
---	---------

CHAPTER V

DECAY IN BUILDING STONES : PHYSICAL OR MECHANICAL PRO- CESSES — CHEMICAL PROCESSES — ATMOSPHERIC POLLUTION — NATURAL JOINTS, CLEAVAGE PLANES, AND CURRENT BED- DINGS IN STONES — POROSITY OF STONES — STRUCTURAL DEFECTS IN BUILDINGS — SETTLEMENTS — OPENING UP OF JOINTS — PRESSURE — WEATHERINGS — DAMP-PROOF COURSES — ROOFS — BALCONIES — BAD BRICKS — MORTARS — CASEMENTS — ENRICHMENTS — FALL PIPES — CRAMPS AND DOWELS — PHYSICAL PROCESSES INVOLVED IN DECAY — SOLUTION — CHANGES IN MOLECULAR VOLUME — GROWTH OF CRYSTALS — "SALTS" — ATTRITION — EXPANSION AND CONTRACTION — FREEZING OF WATER IN STONES — PRESSURE PRODUCED BY PLANTS — HAND WORKING <i>v.</i> MACHINE WORKING OF STONE — CHEMICAL PROCESSES INVOLVED IN THE DECAY OF BUILDING STONES — ACTION OF ACIDS — ACTION OF CHEMICAL SALTS — SOLUTION — HYDRATION — OXIDATION — DEOXIDATION — ACTION OF BACTERIA — HYDROFLUORIC ACID — AND THE SILICOFLUORIDES — CAUSTIC SODA — SOAPS - -	128-207
--	---------

CHAPTER VI

PRESERVATION OF BUILDING STONES : CLEANING PROCESSES — DRY PROCESSES — WET PROCESSES — STEAM CLEANING	208-219
--	---------

CONTENTS

xi

CHAPTER VII

	PAGES
PRESERVATION OF BUILDING STONES (<i>continued</i>): RESTORATION—	
STONE PRESERVATIVES—THE PERFECT STONE PRESERVATIVE	
—CONSOLIDATION PROCESSES—SILICON ESTER—POTASSIUM	
AND SODIUM SILICATES—SODIUM SILICATE AND HYDRO-	
CHLORIC ACID—SODIUM SILICATE AND CALCIUM CHLORIDE—	
SODIUM SILICATE AND ARSENIC ACID—HYDROFLUOSILICIC	
ACID—HYDROFLUOSILICIC ACID AND BARYTA WATER—THE	
SILICOFLUORIDES—BARIUM HYDRATE OR BARYTA SOLUTION	
—(CHURCH'S PROCESS)—RESIN SOLUTIONS—METALLIC SALTS	
OF THE FATTY ACIDS—SOLUTIONS OF SHELLAC—WATER-	
PROOFING PROCESSES—PARAFFIN WAX—VEGETABLE OILS—	
COLLOIDAL SOLUTIONS OR SUSPENSIONS—MARSH'S PROCESS—	
LIMEWASHING " " " " "	220-259
INDEX " " " " "	261-269

LIST OF ILLUSTRATIONS

FIG.		FACING PAGE
1.	ANCASTER STONE (FREE BED) - - -	35
2.	ANCASTER STONE (FREE BED). MAGNIFIED SECTION -	36
3.	ANCASTER STONE (FREE BED). MAGNIFIED SECTION -	36
4.	MONK'S PARK STONE - - - -	45
5.	MONK'S PARK STONE. SECTION MAGNIFIED 30 DIAMETERS -	46
6.	MONK'S PARK STONE. SECTION MAGNIFICATION 5 -	46
7.	COTSWOLD DALE STONE - - - -	60
8.	CORSEHILL STONE. SECTION MAGNIFIED 30 DIAMETERS -	62
9.	CORSEHILL STONE. SECTION MAGNIFICATION 5 -	62
10.	DOULTING STONE (BRAMBLE DITCH OR FINE BED) -	65
11.	DOULTING STONE (CHELYNCH BED) - - -	65
12.	DOULTING STONE (CHELYNCH BED). SECTION MAGNIFIED 30 DIAMETERS - - - -	66
13.	DOULTING STONE (CHELYNCH BED). SECTION MAGNIFICA- TION 5 - - - -	66
14.	FOREST-OF-DEAN STONE (GREY). SECTION MAGNIFIED 30 DIAMETERS - - - -	68
15.	FOREST-OF-DEAN STONE (GREY). SECTION MAGNIFICA- TION 5 - - - -	68
15a.	FOREST-OF-DEAN STONE (GREY) - - - -	69
16.	HAM HILL STONE (YELLOW BED) - - - -	73
17.	HOLLINGTON STONE (RED) - - - -	77
18.	HOLLINGTON STONE (RED). SECTION MAGNIFIED 30 DIA- METERS - - - -	78
19.	HOLLINGTON STONE (RED). SECTION MAGNIFICATION 5 -	78
20.	HOPTON WOOD STONE. SECTION MAGNIFIED 30 DIAMETERS -	80
21.	HOPTON WOOD STONE. SECTION MAGNIFICATION 5 -	80
22.	KENTISH RAG STONE. SECTION MAGNIFIED 40 DIAMETERS -	83
23.	KETTON STONE - - - -	83
24.	KETTON STONE. SECTION MAGNIFIED 30 DIAMETERS -	85
25.	KETTON STONE. SECTION MAGNIFICATION 5 -	85
26.	KETTON STONE. PORTION OF SECTION HIGHLY MAGNIFIED -	86
27.	LECKHAMPTON STONE (SHELL BED) - - -	88
28.	MANSFIELD STONE (RED) - - - -	88
29.	MANSFIELD STONE (RED). SECTION MAGNIFIED 30 DIAMETERS	90
30.	MANSFIELD STONE (RED). SECTION MAGNIFICATION 5 -	90
31.	MINCHINHAMPTON STONE - - - -	92
32.	NAILSWORTH STONE - - - -	92
33.	PORTLAND STONE (WHIT BED) - - - -	94
34.	PORTLAND STONE (WHIT BED). SECTION MAGNIFIED 30 DIA- METERS - - - -	96
35.	PORTLAND STONE (WHIT BED). SECTION MAGNIFICATION 5 -	96

FIG.		FACING PAGE
36.	STORETON STONE . - - - - -	106
37.	WELDON STONE - - - - -	106
38.	RUBISLAW GRANITE. SECTION MAGNIFIED 30 DIAMETERS -	125
39.	RUBISLAW GRANITE. SECTION MAGNIFICATION 5 -	125
40.	SHAP GRANITE - - - - -	126
41.	SHAP GRANITE. SECTION MAGNIFIED 30 DIAMETERS -	127
42.	SHAP GRANITE. SECTION MAGNIFICATION 5 -	127
43.	WEATHERED HAM HILL STONE - - - - -	137
44.	DECAYING RED MANSFIELD STONE - - - - -	153
45.	DECAYING TADCASTER STONE - - - - -	154
46.	DECAYING TADCASTER STONE - - - - -	156
47.	INTENSIVE DECAY OF TADCASTER STONE - - - - -	158
48.	DECAYING TADCASTER STONE - - - - -	160
49.	DECAYING TADCASTER STONE - - - - -	162
50.	BATH STONE, BEFORE COMMENCING EXPERIMENTS -	208
51.	BATH STONE, AFTER USE OF STEAM - - - - -	208
52.	BATH STONE, AFTER USE OF STEAM AND NON-INJURIOUS CHEMICAL - - - - -	210
53.	BATH STONE, AFTER USE OF STEAM, CHEMICAL AND WIRE BRUSH - - - - -	210
54.	PORTLAND STONE, BEFORE COMMENCING EXPERIMENTS -	212
55.	PORTLAND STONE, AFTER USE OF STEAM - - - - -	212
56.	PORTLAND STONE, AFTER USE OF STEAM AND NON-INJURIOUS CHEMICAL - - - - -	214
57.	PORTLAND STONE, AFTER USE OF STEAM, CHEMICAL AND WIRE BRUSH - - - - -	214
58.	RED MANSFIELD STONE, BEFORE EXPERIMENT - - - - -	216
59.	RED MANSFIELD STONE, AFTER USE OF STEAM - - - - -	216
60.	RED MANSFIELD STONE, AFTER USE OF STEAM AND CHEMICAL	218
61.	RED MANSFIELD STONE, AFTER USE OF STEAM, CHEMICAL AND WIRE BRUSH - - - - -	218
62.	RED HOLLINGTON STONE, BEFORE EXPERIMENT - - - - -	220
63.	RED HOLLINGTON STONE, AFTER USE OF STEAM - - - - -	220
64.	RED HOLLINGTON STONE, AFTER USE OF STEAM AND CHEMICAL - - - - -	222
65.	RED HOLLINGTON STONE, AFTER USE OF STEAM, CHEMICAL AND WIRE BRUSH - - - - -	222

LIST OF TABLES

TABLE	PAGE
I. ANNUAL SOOT FALL IN TONS PER SQUARE MILE IN VARIOUS CITIES - - - - -	130
II. ACIDITY FIGURES OF VARIOUS CLASSES OF SOOT -	131
III. VARIATION IN ATMOSPHERIC POLLUTION -	132
IV. ANALYSIS OF CRYSTALLINE INCRUSTATION -	156
V. ANALYSIS OF STONE FROM LINCOLN CATHEDRAL -	157
VI. EXPANSION OF BUILDING STONES - - -	161
VII. MEAN COEFFICIENT OF CUBICAL EXPANSION -	161
VIII. RESULTS OF EXPERIMENTS ON BUILDING STONES	167
IX. RESULTS OF EXPERIMENTS ON BUILDING STONES	168
X. ANALYSIS OF SEA WATER - - - -	183
XI. SOLUBILITY OF MINERALS IN CARBONIC ACID -	191

BUILDING STONES: THEIR PROPERTIES, DECAY, AND PRESERVATION

CHAPTER I

THE need of a knowledge of the chemical and physical properties of the materials used in the construction of buildings is becoming more and more felt by the architect, building contractors, and others interested, not only for its value in enabling a correct usage of these materials, but from the point of view of practical economics. Among the many materials used in the building industry are the building stones, and it is generally admitted that at least some acquaintance with their geology, physics, and chemistry, and their general behaviour in practice, is desirable, and those who have attempted to obtain that knowledge have undoubtedly found it somewhat difficult to do so, owing to the fact that there is little work published on the subject, and what there is, is distributed chiefly in the form of scientific papers or referred to in various textbooks.

In this little book an attempt has been made to deal scientifically and as simply as possible with the chief of the building stones, touching upon their geology, physical and chemical properties, the causes of their decay and preservation. The building stones are natural products, and in order to understand intelligently their properties it is necessary to know something of how they were formed. This knowledge can only be acquired by a study of geology. It is not possible, however, in this book, to deal with the geology of the subject fully, and therefore the reader is referred to special textbooks, the names of which are mentioned in the bibliography at the end of this chapter.

The science of geology cannot be properly studied from books or in laboratories—it is necessary to supplement these methods by work in the “field”; and to the reader of this

work it is recommended that he visit as many stone quarries as possible after becoming acquainted with an elementary knowledge of geology. This will help him not only to obtain accurate ideas in regard to the way in which various rocks used for building stone have been laid down in the geological ages, but also to become acquainted with the means of quarrying the stone, and further he will get some idea, by examining some of the exposures which have not been quarried, how the stone may behave when it is subjected to the action of the weather. It should be remembered, however, that full information in regard to this behaviour cannot be obtained in this way, because a stone which may weather fairly well in the atmosphere surrounding a quarry will decay comparatively rapidly in the polluted atmosphere of a city.

The structural characters of rocks vary much according to their mode of origin, and the natural processes of formation may be conveniently divided into three classes, as under:

- (a) Generation by heat: Igneous.
- (b) Formed by the agency of water: Sedimentary.
- (c) Produced by an alteration brought about by heat, pressure, or crushing of igneous or sedimentary rocks: Metamorphic.

For the benefit of the reader who is unacquainted with geology, the following brief description of these three classes is given.

Igneous.—Those rocks that have been formed by the consolidation of molten rock substances are called igneous rocks, and they are divided into three groups, viz.:

- | | | |
|--------------------------------------|---|---|
| (a) Plutonic ¹ or Abyssal | { | Intrusives— <i>i.e.</i> , rocks that have consolidated below the surface of the earth's crust. |
| (b) Hypabyssal | | |
| (c) Volcanic .. | { | Extrusives— <i>i.e.</i> , rocks that have consolidated on cooling above the surface of the earth's crust. |
| | | |

¹ Pluto = God of the lower regions.

The difference between plutonic, hypabyssal, and volcanic rocks is more of a physical than a chemical nature. They both originate from the same source, but in the process of cooling the conditions have been different. In the case of the plutonic rocks the solidification of the molten material took place under conditions imposing a slow rate of cooling, accompanied by considerable pressure and the presence of occluded water, and this yielded a highly crystalline and coarse-grained texture, whilst the molten magma which produced volcanic rocks upon solidification was subjected during this process to a rapid cooling accompanied by diminished pressure and consequent loss of water, resulting in a rock of more or less vitreous character and often highly cellular in structure. The hypabyssal rocks hold an intermediate position between plutonic and volcanic rocks. They occur in smaller masses than the plutonic, and have a less coarsely crystalline structure. From volcanic rocks they differ essentially in the fact that they are intrusive, occurring as dykes, sills, etc., so that cooling has taken place more slowly, with consequent effect upon the crystalline structure of the rocks. Rocks of hypabyssal and volcanic origin are not very much used in this country for building purposes. There are one or two which are used locally and which may be named. These are Melrose Agglomerate and "Alloa Granite" (a dolerite), which has been used in London as well as locally. The plutonic rocks are very much more largely used in the building industry, and the chief rock in this division is granite, of which many different types exist.

Because the molten magma from which the plutonic and volcanic rocks originated came from the depths of the earth, the reader must not be led to hold the view that these rocks are older than some of the sedimentary rocks. They are often younger, or contemporaneous, having been pushed between the strata of the sedimentary rocks, forming large dome-shaped masses and what are known as intrusive sheets. Invariably a plutonic or hypabyssal magma must be younger than the rocks into which it is intruded, and in

which it brings about intensive alteration along a zone of contact. Volcanic rocks may be strictly contemporaneous with the rocks over which they have been extruded only when the eruptions took place in areas where deposition was in progress. Rocks reposing in a lava flow must, of course, be younger than the volcanic rocks beneath them. Whilst there is no doubt that the primary surface of the earth was formed by the cooling of a molten magma, producing in all probability rocks which would come under the class known as igneous, these primary rocks have eventually become covered with rocks of a sedimentary character, after a process of denudation, and between the strata of these sedimentary rocks, owing to eruptive action, molten magma was intruded, which when cool would form an igneous rock of a later age than the sedimentary rocks between which it had been forced.

Sedimentary Rocks.—In defining sedimentary rocks the term “sediment” must be employed in its widest sense, and it must mean, therefore, all those materials which are laid down or deposited through the agency of water, through chemical or biological agencies, or by the aid of wind.

In the outer layer of the earth’s crust there are more sedimentary¹ than any other type of rocks. Now at the outset it must be clearly understood that the sedimentary rocks are not composed of original or primary material; all of them have been derived from some source, the nature of which, if in its actual site, can usually be determined; they

¹ In a work on “The Composition of the Earth’s Crust” (U.S. Geol. Surv. Prof. Paper 127), Clarke and Washington, assuming a thickness of ten miles for the crust, estimate the proportion of rocks of different classes to be as follows:

Igneous rocks	..	..	..	95·00	per cent.
Shales	..	..	..	4·00	„ „
Sandstones	..	..	..	0·75	„ „
Limestones	..	..	..	0·25	„ „

Since sedimentary rocks cover such a large area of the earth’s land surface, it is obvious that they form merely a thin film covering the igneous rocks beneath.

are built up of detritus, formed by the breaking down or decomposition of older and very often igneous rocks. The chief characteristic of the sedimentary rocks is that they are stratified—that is to say, they have been deposited, usually in water (sometimes in air), in layers; layer above layer, and bed upon bed being deposited, and each of these layers or beds marks an interval in the progress of deposition. It is convenient to divide the sedimentary rocks into three classes according to the mode of origin or method of formation:

- (a) Those mechanically formed.
- (b) Those organically formed.
- (c) Those chemically and biologically formed.

It should be noted that in these divisions there is a certain amount of overlapping; for instance, in the mechanically formed rocks the fragments or clastic material may be cemented together by a chemically formed cement.

Mechanically formed Rocks.—In this group, so far as building stones are concerned, we have the sandstones (and incidentally sands and gravels). The sandstones are known also as arenaceous¹ rocks, and, as will be learned later, they consist of small grains of various minerals, which are derived from older rocks, cemented together by silica, calcium carbonate, dolomite, or iron oxide; sometimes the cementing material is a mixture of two or more of these substances. The shape of the sand grains varies, some being angular, others sub-angular, whilst others are rounded, and this variation in shape indicates in a general way how they have been formed before becoming bound together. Those which are distinctly angular are likely to be of glacial origin, the sub-angular grains were formed in moving water, and the rounded grains owe their shape to attrition caused by wind. These stones are generally laminated and frequently false-bedded, which indicates that they have been laid down in shallow water disturbed by currents. Speaking generally,

¹ Lat. *arena* = sand.

when sandstones have no very marked current-bedding and can easily be cut into blocks, they are called freestones, but when they can be split easily into slabs along the bedding planes they are termed flagstones. There are certain sandstones the sand grains of which are cemented together with clay, and which have become consolidated by pressure only. These are called mudstones, and they are very easily disintegrated by washing with water.

The cementing material has either been laid down with the sand grains at the time of their deposition, or has subsequently been introduced by water permeating the sand. The colours of the sandstones are determined, to a very large extent, by the nature of the cementing material; the various shades of red, yellow, and brown are produced by oxide of iron, and those of a greenish tint by the mineral glauconite.

The sandstone deposits are characteristically shallow water deposits, and those which have been formed in the seas of all geological ages almost always contain a certain amount of fragments of shells and corals, and in many cases moderately large quantities of glauconite. Sandstones of estuarine origin closely resemble those laid down in the sea, but there is, however, a tendency for them to contain a certain amount of muddy or clayey matter, and those of fresh-water origin differ only in the fact that they do not contain any disintegrated shells of marine organisms: a red or purple colour in sandstones is often an indication of fresh-water origin.

Organically formed Rocks.—The only group in this class which concerns building stones is that which includes the calcareous rocks. Speaking broadly, the limestones, which occur in this class, are formed from the disintegrated remains of marine organisms, or rather the shells of these animals. The calcareous remains of some types of algæ may be included also. As most of these organisms live in clear water, free from sand and mud, the limestones are nearly always clean and free from impurities. Chalk (Beer stone, Totternhoe stone, Clunch stone) is included in this group. Some

of the limestones were laid down in sea water, and others in fresh water; as a matter of fact, some of the tertiary limestones are composed chiefly of the shells of fresh-water and land snails. Limestones occur in far-reaching deposits or beds, which are not usually laminated, and rarely false bedded. It is very probable that a few of our limestones were derived directly from organic remains, but most are, in part, at least, chemical deposits.

The colour of the limestones is due, chiefly, to larger or smaller quantities of oxide of iron, or small quantities of finely divided carbonaceous matter, which in some cases assists the matrix as a binding or cementing substance.

The dolomites or magnesian limestones can be classed among the organically formed rocks. They may have been deposited first of all as ordinary limestones, and then partially changed by the chemical action of magnesium salts in the saline water covering it, a portion of the calcium carbonate being replaced by magnesium carbonate.

Chemically and Biologically formed Rocks.—In this class also the only rocks which are of use in the building industry are the limestones. It is interesting to note that the substance which is most abundantly deposited by chemical precipitation is calcium carbonate, which is the chief constituent of the limestones. Among the stones of this class are the travertines or calcareous tufas and the oolitic limestones. In the case of the former the calcium carbonate is deposited from water which issues in the form of springs from limestones or other rock abounding in this material, and which carries in solution calcium bicarbonate. As this water reaches the surface carbon dioxide is liberated, and calcium carbonate is deposited in the form of a white precipitate. This accumulates, and in time forms masses of rock. The travertines used in the building industry are of modern origin, and they occur in connection with the Purbeck beds of Dorset, the rhætic and lias, and the Burdie House limestones of Carboniferous age in Scotland.

The oolitic limestones are only partially formed by

chemical means, and they are a type of what may be termed secondary limestones. The oolites contain nuclei composed of shell fragments, particles of mud, or sand grains, which have been broken up by the action of moving water and then covered with calcium carbonate by decomposition. The calcium carbonate is deposited as concentric layers in the form of aragonite (originally). The oolitic limestones may also contain, among the oolites, disintegrated shells, etc., the whole mass being bound together by calcite. Some magnesian limestones may have been precipitated direct as dolomite in inland seas subject to rapid evaporation. Dolomites originating in this way are almost always associated with beds of rock salt, gypsum, etc.

In regard to the matter of biological action it is thought by Drew, Killerman, and Vaughan,¹ that bacterial processes have played an important part in the formation of the non-fossiliferous limestones of geological ages.

The following classification of strata, in addition to its geological value to the reader, may be useful in indicating the types of stones which are found in the various series.

<i>Era.</i>	<i>System.</i>	<i>Series.</i>	<i>Types of Stones Found.</i>
Cainozoic or Tertiary	Post-pliocene Pliocene Miocene Oligocene Eocene		
	Cretaceous	Upper Cretaceous Middle Cretaceous Lower Cretaceous	Merstham Firestone (upper greensand). Reigate stone. Beer stone.
Mesozoic or Secondary	Jurassic	Upper Oolites	Wealden stone, Kentish Rag stone, Clunch stone, Totternhoe stone.
		Middle Oolites	Portland stone (Whit-bed, Base-bed, and Roche-bed), Chilmark stone, Purbeck Cliff stone, Purbeck free-stone, Tisbury stone. Headington stone, Caen stone.

¹ See Professional Paper 113, p. 76: Department of the Interior, United States Geological Survey.

PROPERTIES, DECAY, AND PRESERVATION 25

<i>Era.</i>	<i>System.</i>	<i>Series.</i>	<i>Types of Stones Found.</i>
Mesozoic or Secondary	Jurassic	Lower Oolites	Ham Hill stone, Doultling stone, Painswick stone, Nailsworth stone, Leckhampton stones, Weldon stone, Ketton stone, Clipsham stone, Ancaster stone, St. Aldhelm Box stone, Corsham Down stone, Corsham stone, Combe Down stone, Monk's Park stone, Minchinhampton stone.
	Triassic	Lias Rhætic Keuper	Blue Lias stone. Quarella stone. Red Hollington stone (white and mottled), Penkridge stone, Storeton stone.
		Bunter	St. Bees stone, Aspatria stone, Corsehill stone, Closeburn stone, Rainhill stone, Woolton stone.
Newer Pal- æozoic or Deutozoic	Permian	Upper	
		Middle	Mansfield Woodhouse stone, Bolsover Moor stone, Anston stone, Huddlestons stone, Park Nook stone.
	Carboniferous	Lower	Red and white Mansfield stone, Roche Abbey stone.
		Coal Measures	Bolton Wood stone, Robin Hood stone, Park Spring stone, Bristol Pennant stone, Grey Forest-of-Dean stone, Windy Nook stone, Howley Park stone.
		Millstone Grit	Darley Dale stone, Hall Dale stone, Bramley Fall stone, Kenton stone, Minera stone, Shamrock stone.
		Carboniferous Limestones	Hopton Wood stone, Prudham stone, Craighleith stone, Hailes stones, Blaxter stone, Heddon stone.
	Devonian	Upper Old Red Sandstone Middle Lower	Caithness stone, Wilderness stone.
Older Pal- æozoic or Protozoic	Silurian		
	Ordovician Cambrian Archæan		

In regard to the granites the geological age varies; at one time it was supposed that the granitic rocks were the oldest, but careful field work has proved that granites have been formed at several geological periods from pre-Cambrian times down to the Tertiary period. For instance, the granites of Cornwall and Devon are more recent than the Carboniferous period, and the granite of the Alps of Savoy is more recent than the Jurassic, whilst that of the Eastern Pyrenees is more recent than the White Chalk. There are, however, granites of very great age, such as those found in Scandinavia, the Highlands of Scotland, and in some parts of Ireland. Shap granite belongs to Old Red Sandstone times, the Peterhead granite is of post-Silurian age, while the granite rocks of the western Isles of Scotland are of Tertiary age.

To assist the reader in understanding some of the various reactions which take place during the weathering and decay of stone, the following brief particulars of the chief minerals and other substances which occur in those rocks from which building stones are obtained may be found useful.

Calcite, CaCO_3 .—This compound, which is very often incorrectly termed carbonate of lime, crystallizes in the hexagonal system. Common forms are flat or acute rhombohedra, sharp-pointed scalenohedra, prism, and flat tablets. The crystals are usually colourless and sometimes white, or, due to impurities, yellow, red, or brown. They have a vitreous lustre, may be transparent or opaque, possess a perfect rhombohedral cleavage, and break with a conchoidal fracture. Calcite possesses a hardness of 3, and a specific gravity of 2.7. It is nearly insoluble in water; 100 parts of this solvent dissolves 0.0018 part of the compound at 15° C. Mineral acids act upon it readily with effervescence due to the escape of carbon dioxide.

Magnesium Carbonate, MgCO_3 (Magnesite).—This salt crystallizes in the hexagonal system with rhombohedral symmetry. The crystals are colourless, white, or yellow, of transparent to opaque appearance, and they possess a

perfect rhombohedral cleavage. Magnesium carbonate has a hardness between 4 and 4·5, and its specific gravity varies between 2·9 and 3·05. For all practical purposes it can be considered as insoluble in water, but it is acted upon by mineral acids, although not so vigorously as is calcium carbonate. Hydrochloric acid acts upon it more readily than sulphuric acid.

Dolomite, $\text{CaMg}(\text{CO}_3)_2$ or $\text{MgCO}_3 \cdot \text{CaCO}_3$.—Dolomite is also known as pearl spar or bitter spar, and it crystallizes in the hexagonal system. Characteristic crystals are saddle-shaped with curved faces. Crystals of this compound may be colourless, white, yellow, or brown, and less common in blue, green, or red, and they possess a perfect rhombohedral fracture. The crystals are brittle, possess a hardness of 3·5, and a specific gravity of 2·85. They are decomposed by warm mineral acids with effervescence, and are less readily attacked than calcite. Dolomite is practically insoluble in water.

Aluminium Oxide, Al_2O_3 (Alumina, Corundum).—This compound crystallizes in the rhombohedral system, and occurs colourless or tinted with various metallic oxides. It is also found in nature in the amorphous condition. Aluminium oxide fuses at about $2,000^\circ \text{C}$., possesses a hardness of 9, and its specific gravity varies from 2·8 through 3·75 to 4·1. (The specific gravity of corundum is 4.) It is insoluble in water, and is acted upon with difficulty by mineral acids.

Iron Oxides.—These substances occur in nature in several forms, among which are magnetite, limonite, hæmatite.

Magnetite, $\text{Fe}_2\text{O}_3 \cdot \text{FeO}$.—This compound crystallizes in the cubic system and frequently occurs in very perfect octahedra or dodecahedra. It possesses an iron-black colour and a metallic lustre, and its fracture is conchoidal to uneven. Its hardness varies between 5·5 and 6·5, and its specific gravity is 5·2. One of its characteristics is its magnetic property, which is very pronounced. Water does not dissolve it, but in the powder form it is easily soluble

in hydrochloric acid, and when exposed to varying temperatures and moisture it slowly decomposes, giving rise to hydrated sesquioxides.

Limonite, $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$, generally occurs in massive or earthy conditions of a dark brown to yellow colour; the common yellow and brown colours of sandstones and many other rocks are generally due to the presence of this substance. It is a comparatively soft to moderately hard mineral, possessing a hardness of 1 to 5.5, the latter in the case of the compact varieties, and its specific gravity varies between 3.3 and 4. Limonite is insoluble in water, but dissolves slowly in hydrochloric acid.

Hæmatite, Fe_2O_3 , is usually found in a massive condition possessing a compact granular texture, or in nodular masses with a smooth exterior and a radiating internal structure, and its colour is iron-black, brown, or bronze-red. It should be noted that in the amorphous or crypto-crystalline condition it acts as the cementing substance of some sandstones, and it is also responsible for the red colour of many rocks. Hæmatite possesses a hardness between 3 and 6, and a specific gravity of 5.19 to 5.3. It is insoluble in water, but is soluble in concentrated hydrochloric acid.

Ferrous Carbonate, FeCO_3 (Siderite, Chalybite, Clay Iron-stone).—This compound crystallizes in the rhombohedral form, and in colour it is usually grey, or brown, becoming darker on exposure. It is also found in the amorphous or concretionary form, which is bluish when fresh, and which on exposure changes its colour to brown. The crystals have a conchoidal fracture. Ferrous carbonate has a hardness of 3.5 to 4.5, and its specific gravity varies between 3.7 and 3.9. Hot mineral acids will dissolve it moderately rapidly with the evolution of carbon dioxide. It is attacked by cold mineral acids, but not so readily as calcite, and it is insoluble in water.

Glaucinite.—This substance is a decomposition product of marine origin. It is formed in modern sediments inside the tests of foraminifera. Most glauconite sands have

arisen in this way. Glauconite can be considered as a secondary mineral, and it is a somewhat variable compound composed of the silicates of aluminium, iron, potassium, magnesium, and calcium, and the amounts of these salts may vary. Glauconite occurs in the amorphous condition, and is almost always impure. It is opaque in appearance and yellowish to dark green in colour. Water does not dissolve it, and it is practically insoluble in acids. On the scale of hardness its position is 2, and its specific gravity varies between 2.2 and 2.4.

Quartz, SiO_2 .—This is the most abundant mineral in the earth's crust. It crystallizes in the hexagonal system, and it has no cleavage; its fracture is conchoidal. The crystals of quartz may occur colourless, and in a variety of colours, among which may be mentioned green, yellow, brown, blue, pink, and grey. It has a vitreous lustre, a hardness of 7, and a specific gravity of 2.65. Quartz is insoluble in water, dissolves with difficulty in caustic potash, is not attacked by hydrochloric, nitric, or sulphuric acids, but is soluble in hydrofluoric acid.

Felspars.—The felspars are a family of minerals which play an important part in the construction of rocks. They occur primarily in those of igneous formation, but are found in all those which are built up of disintegrated igneous rocks. Among the felspars may be named orthoclase and microcline (potash felspars), albite (soda felspar), anorthite (lime felspar), oligoclase (silicate of aluminium containing calcium and sodium oxides). For the purpose of this book the felspars can be considered as anhydrous silicates of aluminium containing varying amounts of calcium, potassium, or sodium. Their chemical and physical properties are somewhat closely related. One common characteristic is that of possessing two easy cleavages inclined to one another at an angle approximating 90° . There is a close relationship in optical properties, and a great similarity in colour. Crystals of felspar may be transparent, or white, or yellowish-pink, or red, and at times greenish in colour,

and all varieties may be opaque through the presence of impurities or due to decomposition. The hardness varies between 5 and 6·5, and the specific gravity between 2·2 and 2·75. The fracture of the felspars is generally conchoidal. Water does not dissolve the felspars, but some of them are decomposed by hydrochloric acid with the precipitation of silica (anorthite), whilst others are not (oligoclase).

Mica.—The micas are hydrated silicates of aluminium and potassium, sodium or lithium, and in some varieties iron and magnesium occur. They crystallize in the monoclinic system, the crystals having the form of six-sided tablets. Mica possesses a very perfect cleavage which permits of its separation into sheets or laminæ of extraordinary thinness. These laminæ are elastic, and this property distinguishes mica from other allied minerals, such as talc. The hardness of the micas varies between 2 and 3, and the specific gravity between 2·76 and 3·2. For practical purposes the micas may be separated into two subdivisions, the white or light-coloured micas, the chief of which is muscovite, and the black or dark-coloured micas, the most important of which is biotite. The former variety of mica is not attacked by hydrochloric acid, whilst the latter variety is attacked by this acid, especially if it is hot. Biotite is particularly subject to atmospheric decomposition, and on this account does not occur to any very great extent as a secondary constituent of rocks.

Hornblende—



Hornblende is essentially metasilicate of calcium, magnesium, iron, and aluminium. What is known as common hornblende is the aluminous variety, and this mineral is a constituent of many kinds of granite. It also occurs in some of the sandstones in a fragmentary condition. Hornblende crystallizes in the monoclinic system, and twinning is frequent. It is found in several shades of green, and also in dark brown and black, and there is a colourless variety;

the crystals may be transparent or opaque. Cleavage fragments are generally more or less slender; far more so than augite. The hardness of this mineral varies between 5 and 6, and the specific gravity between 2·9 and 3. All the varieties of hornblende are insoluble in water, and resist the action of acids, excepting hydrofluoric.

Augite.—Augite is essentially a modification of hornblende, and its composition is similar to this substance. It differs slightly in the form of its crystals, and occurs in various shades of green to colourless, and also in shades of brown to black. It may be transparent or opaque, and it possesses a prismatic cleavage of 88° , which distinguishes it from hornblende with a cleavage angle of $55\cdot5^\circ$. Its hardness varies from 5 to 6, and its specific gravity is generally between 3·2 and 3·6. Water does not dissolve it, and like hornblende it resists the attack of all acids but hydrofluoric.

Rutile (Titanium Dioxide), TiO_2 .—Rutile crystallizes in the tetragonal system, and it is also found in massive forms. Its colour is reddish-brown, and it possesses a lustre which is usually metallic. The position of this substance on the scale of hardness is 6·5, and its specific gravity is 4·3. Rutile is insoluble in water and in acids, and is a compound of extraordinary stability. On this account it is found in almost all sands and in many sandstones.

Zircon, $\text{ZrO}_2\cdot\text{SiO}_2$.—This substance is a silicate of zirconium. It crystallizes in the tetragonal system, and is isomorphous with rutile. Zircon is transparent to opaque, and its colour varies, the chief being dark brown; orange, yellow, red, pale green, and grey zircon occurs in nature. It has a conchoidal fracture, a hardness of 7·5, and a specific gravity of 4·7. Like rutile it is an almost indestructible mineral, being insoluble in water, and attacked only with difficulty by hot sulphuric acid. It is a very common ingredient of sands and sandstones.

Garnet.—The garnets are silicates of aluminium, iron, chromium, calcium, and magnesium, and they vary in

colour, this being due to the presence or absence of one or other of the elements just mentioned. For instance, the blood-red garnet contains iron, magnesium, calcium, aluminium, and chromium silicates, whilst in the constitution of the green garnet are only chromium and calcium silicates. All garnets crystallize in the regular system, the most common form being the rhombohedric dodecahedron, and the crystals may be transparent or opaque. The hardness is between 6.5 and 7, and the specific gravity varies between 3.4 and 4.3. Garnets are insoluble in water, and are attacked with difficulty by hydrochloric acid.

Tourmaline.—This substance is hydrated borosilicate of sodium, magnesium, and aluminium. Tourmaline crystallizes in the hexagonal system, and its characteristic fracture is subconchoidal. Its usual colour is black or dark brown, but it sometimes occurs in various tints of red, blue, and green, and even colourless crystals are known. Its hardness is 7, and its specific gravity varies between 3 and 3.2. It is insoluble in water and in acids.

Ilmenite.—This compound is known also as titaniferous iron ore, and it may be represented by the formula $\text{FeO} \cdot \text{TiO}_2$, although it sometimes contains Fe_2O_3 . It crystallizes in the hexagonal system, and is isomorphous with hæmatite. In addition to a pronounced crystalline form it occurs in deposits of a massive structure. Its colour is iron-black, it is opaque, and its fracture is conchoidal. The hardness of ilmenite varies between 5 and 6, and its specific gravity is between 4.5 and 5.3. It should be noted that the specific gravity increases with the Fe_2O_3 content. Water does not dissolve it, but the finely powdered material is soluble in boiling hydrochloric acid.

Sphene, $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$.—Sphene is titanosilicate of calcium, and it crystallizes in the monoclinic system. Its colour is olive-brown, and it possesses a distinct prismatic cleavage, its fracture being subconchoidal. The hardness of sphene is 5, and its specific gravity is 3.5. It is insoluble in water, and hydrochloric acid decomposes it with difficulty.

Apatite.—This name is given to the chlorophosphate of calcium, $3\text{Ca}_3(\text{PO}_4)_2\cdot\text{CaCl}_2$, or fluorphosphate of calcium, $3\text{Ca}_3(\text{PO}_4)_2\cdot\text{CaF}_2$. Apatite crystallizes in the hexagonal system, and it frequently occurs in the form of elongated prisms. Usually it is colourless, but forms occur tinted green, blue, or violet. It possesses an imperfect cleavage, and its fracture is conchoidal. Its position on the scale of hardness is 5, and its specific gravity is 3.22. Apatite is insoluble in water, but is attacked by hydrochloric and nitric acids; quite readily by the latter substance.

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CHAPTER II

THERE are a great variety of stones employed for building purposes, and as many as possible have received attention in this book. For the convenience of the reader the descriptions of them are given in alphabetical order, either under the heading of limestones, sandstones, or granites, according to their mineralogical characters.

It will be readily understood that the chemical composition and physical properties of somewhat impure natural products vary to a certain degree, and on this account it is not possible to give other than approximate figures when dealing with these factors.

Ancaster Stone.—This stone is a member of the Lincolnshire Limestone deposits which occur in the Inferior Oolite of the Jurassic system. It is a marine limestone, evidently laid down in a moderately shallow sub-tropical sea, and on this account the beds are subject to frequent variation in their thickness, and in the nature of the sedimentary material of which they are composed. In quarrying this stone two general types are worked—viz., the Weather Bed and the Free Bed.

Weather Bed.—Another name for this stone is Ancaster Rag, and its ground colour is brown, with grey and buff mottling. The brown colour is no doubt due to the comparatively large quantity of oxide of iron (Fe_2O_3) present; this averages about 1.5 per cent. It is coarse-grained but compact, and is distinctly oolitic, containing with the ooliths a large quantity of comminuted shells with some more or less perfect specimens. The stone can be termed crystalline, and there are to be seen a fairly large number of small plates of calcite interspersed throughout the mass, and also some large plates of the same material. These plates constitute to a very large extent the matrix or binding material. Some of the binding material seems to be stained more or less heavily with oxide of iron. In this stone occur occasional small cavities or druses, which are lined with well-formed crystals.



FIG. I.—ANCASTER STONE (FREE BED)

To face p. 35

It should be noted, by the way, that there is also a red weather bed stone, which is light red in colour, very slightly mottled with buff, and inclined to be grey in patches. The structure is markedly oolitic, and the amount of comminuted shells is comparatively small. Large pieces of shell and complete fossils are always present. It is medium-grained, softer than the brown weather bed, but slightly harder than the free bed. There are a few plates of calcite to be seen, and the binding material, which is also of this substance, and the ooliths are strongly stained by oxide of iron. The clay patches which appear in the stone are caused by the admixture of a certain amount of clay or marl with the ooliths.

Free Bed.—The stone from this bed is pale buff or cream in colour, and contains about half the quantity of oxide of iron that is found in the weather bed—viz., about 0.75 per cent. It is fine-grained, comparatively compact, and distinctly oolitic. Intermingled with the ooliths are comminuted shell fragments and a small quantity of almost complete fossils, the whole mass being bound together mainly by crystalline calcite, portions of which occur in thin plates. These plates vary in size, some of them being almost $\frac{1}{2}$ by $\frac{1}{2}$ inch, and they produce a peculiar glistening appearance both on the faced and broken surfaces of the stone. It is not an easy matter to distinguish the oolitic structure on a faced stone (see Fig. 1).

The Ancaster stones work up to a good arris and a comparatively smooth face, and are suitable not only for plain ashlar but for enrichments. They should not be used, however, in towns or cities the atmospheres of which are polluted.

The oolitic structure of this stone is shown beautifully in a thin section examined under the microscope (see Figs. 2 and 3). It will be observed that the ooliths are of a variety of shapes, and some of them have as nuclei fragments of shells, many of which (foraminifera) show the septa and chambers. The concentric structure of some of the ooliths

is still visible, but in the larger number it is not apparent, neither is there a radial structure; the greater number of ooliths appear to have a granular structure. Most of them are stained with oxide of iron, which gives them a brownish colour, some being stained throughout, others on the edges only. They are well separated and are cemented together by crystalline calcite, which in the section has a mosaic appearance.

The Ancaster stones are quarried at the Ancaster and Lindley Quarries, near Ancaster in Lincolnshire.

The approximate chemical composition of the weather bed is given below.

WEATHER BED.

Calcium carbonate (CaCO_3)	..	..	95.99
Magnesium carbonate (MgCO_3)	..	..	1.90
Aluminium oxide (Al_2O_3)	..	..	0.32
Iron oxide (Fe_2O_3)	..	..	1.48
Silica (SiO_2)	..	..	0.11
Water and loss (H_2O)	..	..	0.20

(Prof. Attfield)

FREE BED.

Calcium carbonate (CaCO_3)	..	..	94.96
Magnesium carbonate (MgCO_3)	..	..	2.52
Aluminium oxide (Al_2O_3)	..	..	0.51
Iron oxide (Fe_2O_3)	..	..	0.86
Silica (SiO_2)	..	..	0.10
Water and loss (H_2O)	..	..	1.05

It will be noticed that the free bed, which is the pale quality of Ancaster stone, contains less oxide of iron than the weather bed, which is of a brown colour, and this fact indicates that the darker colour is due to the larger quantity of this oxide.

Figures relating to the physical properties of the Ancaster stones, which are approximate, will be found below.

WEATHER BED.

Specific gravity	..	..	..	2.5
Weight per cub. ft.	..	..	..	156 lbs.
Crushing resistance per sq. ft.	..	..	..	552.6 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	2.45

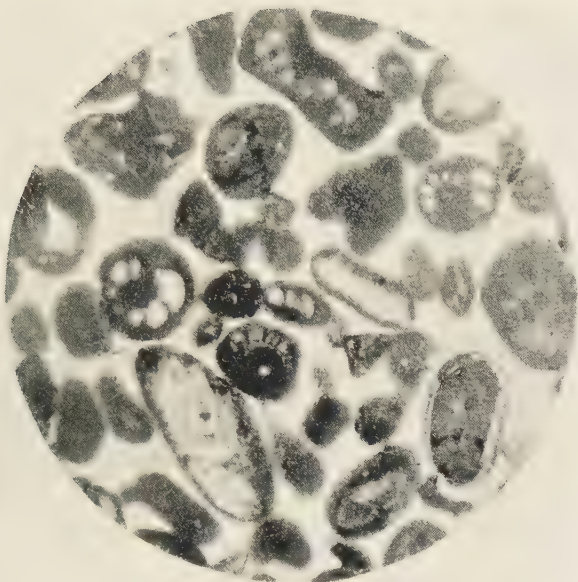


FIG. 2.—ANCASTER STONE (FREE BED)
Section magnified 30 diameters



FIG. 3.—ANCASTER STONE (FREE BED)
Section magnification 5. The white spaces are the crystalline
calcite, which is the binding material

FREE BED.

Specific gravity	..	..	..	2.21
Weight per cub. ft.	..	..	..	136 lbs.
Crushing resistance per sq. ft.	..	..	..	195 tons.
Absorption, per cent. of its dry weight	..	..	..	6.25

The good weathering of Ancaster stone depends almost entirely on the situation of the building in which it is used, and the atmospheres which surround it from time to time. There are several forms of decay exhibited by this stone, the chief of which are scabbing or exfoliation and pitting. In the case of the former, flakes of 1 to 1½ inches in thickness and 12 or more inches long, and even 6 inches wide, are sometimes formed. The cracks, which open at the commencement of the exfoliation process, occur usually along the lines of current bedding, and the pieces which break away are often lenticular in form. When decay in the form of pitting occurs, the surface of the stone becomes covered with a large number of pits, and accompanying this is the formation of irregular grooves, at times 1 or 2 feet in length. This stone weathers back gradually, forming a rough and ragged-like surface, and veins of calcite often weather out in relief. Interior decay of mullions built of Ancaster stone generally takes on the form of falling away in powder, and this is due mainly to the stone becoming wetted on the outside by rain and the evaporation of the moisture in the interior after it has dissolved a small quantity of the stone.

In the polluted atmosphere of towns Ancaster stone seems to behave somewhat erratically; the author knows of buildings, some sixty years of age, which are in quite a good condition, especially when compared with other buildings in the same city between eight and twelve years old which show much badly decayed stone.

The undermentioned approximate prices are for Ancaster stones, free bed and weather bed respectively, fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These

prices are for the London district only; transport and wages would modify them for different parts of the country.

ANCASTER STONE (FREE BED).

Average type commercial building	..	14/6	per	cube	foot.
Fairly ornate church job	..	17/6	„	„	„

ANCASTER STONE (WEATHER BED).

Average type commercial building	..	17/6	per	cube	foot.
Fairly ornate church job	..	21/-	„	„	„

Anston Stone.—This is a magnesian limestone, or dolomite, which occurs in the middle Permian beds of the Permian system. It was in all probability formed in large inland seas of the Permian period, and although its bedding is comparatively regular, the stone is liable to variation. Throughout the mass of stone are to be seen an abundance of minute irregular cavities (druses), many of which are filled with calcite crystals. These cavities are apparently due to shrinkage during dolomitization by the process known as metasomatism; the reduction in volume when calcium carbonate is changed into dolomite is approximately 12 per cent. It is possible that this shrinkage produces almost invisible interstitial rifts in the stone (as well as cavities), and these may be a cause of weakness, especially in regard to weathering, when they occur in quantity. To a very large extent the stone is built up of small dolomite crystals in the form of rhombs, and these are tinted by oxide of iron (Fe_2O_3), which gives the stone a light cream colour. Anston stone can be considered as possessing a fine grain, and on a fresh fracture it appears paler and less crystalline than Bolsover stone. A good arris can be formed on this stone, and it is possible to prepare a good surface on it. For carved work it is quite suitable, provided the stone is carefully selected, and it can be used for exterior dressings. In fixing it should be laid on its natural bed. It is not wise to use this stone in polluted atmospheres.

The approximate chemical composition of Anston stone is given below.

Calcium carbonate (CaCO_3)	..	..	..	..	54·88
Magnesium carbonate (MgCO_3)	..	..	..	..	43·08
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	0·73
Silica (SiO_2)	..	..	..	..	0·56
Water and loss (H_2O)	..	..	..	..	0·75

In regard to the physical properties of this stone, the following particulars will prove useful:

Specific gravity	..	..	..	..	2·12
Weight per cub. ft.	..	..	..	..	134 lbs.
Crushing resistance per sq. ft.	..	..	..	..	302 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	..	7·5

Unless this stone is carefully selected there is a great risk of it weathering badly. This fact appears to be obvious by a comparison between the Anston stone used in the Houses of Parliament and the Museum of Practical Geology, both in London and not very far from each other. In coming to a definite judgment in this matter, however, there are one or two points which should not be overlooked, and these are:

- (a) The Houses of Parliament are situated immediately on the banks of the River Thames and in a comparatively open position from all sides, and therefore the stone in this building will be subjected not only to the action of damp mists which are inevitable in proximity to water, but to the smoke and waste gases from river craft, and also to the foul and polluted atmosphere of London.

The Museum of Geology is so built that it has two frontages only, one in Piccadilly, and one in Jermyn Street, and these, particularly in the case of the Jermyn Street front, can be considered in a more protected position and less liable to attack from atmospheric and other influences.

- (b) The stone in the Houses of Parliament has been wrought and carved, whilst that in the Geological Museum is chiefly in the form of plain ashlar.

In the decay of this stone various states present themselves. Some portions of the stone weather spongy, and eventually the particles fall away in the form of a powder. Exfoliation is another form, the thickness of some of the scabs amounting to nearly $\frac{1}{8}$ inch. Along the lines of current bedding deep grooving also occurs, and some surfaces erode away in the form of pits or cavities. In a number of instances these cavities already exist in the stone in the form of druses, and they become exposed when the thin wall left after machining has weathered away in the course of time. During the decay of this stone it very often appears to swell or expand, and this is due to a growth of crystals between the various current bedding layers, these crystals lifting the layers and thus appearing to increase the bulk of the stone; this form of corrosion is best seen in enrichments. Fuller details in regard to the decay of this and other magnesian limestones will be found in Chapter V., which deals with decay.

Aspatia Stone.—This is a chocolate or dull red coloured sandstone of fine grain. It occurs in the Bunter series of the Triassic system, and is in all probability of estuarine origin. The Bunter deposits are liable to variation both in colour and texture, but Aspatia stone, from a practical point of view, can be considered as uniform in quality and colour. This stone carries a good arris, and works up to a fairly smooth face, and it may be employed for internal and external work, whether carved or plain. The quarries are near Aspatia in Cumberland.

The approximate chemical composition of Aspatia stone is as follows:

Silica (SiO_2)	..	..	..	..	..	85.86
Iron oxide (Fe_2O_3)	..	..	..	..	..	3.72
Aluminium oxide (Al_2O_3)	..	..	..	..	..	5.58
Calcium carbonate (CaCO_3)	..	..	..	..	..	0.17
Magnesium carbonate (MgCO_3)	..	..	..	..	..	0.62
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	2.60
Water and loss (H_2O)	..	..	..	..	..	1.45

Aspatria stone possesses the following physical properties:

Specific gravity	..	..	..	..	1.98
Weight per cub. ft.	..	..	..	..	124 lbs.
Crushing resistance per sq. ft.	..	..	..	..	759.7 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	..	8.7

The two chief forms of decay exhibited by this stone are exfoliation and crumbling to a fine powder. In all but very polluted atmospheres it weathers very well indeed.

Bath Stones.—Under the general term “ Bath stone ” come a number of stones, among which may be mentioned Combe Down stone, Corsham Down stone, Farleigh Down stone, Hartham Park stone, Monk’s Park stone, St. Aldhelm Box Ground stone, and Stoke Ground stone. These stones will be described under their respective names in the order mentioned above.

The Bath stones are obtained from the limestone deposits known as the Great or Bath Oolite series of the Jurassic system, and whilst this deposit extends from the coast of Dorsetshire through Somersetshire, Gloucestershire, Oxfordshire, Northamptonshire, to Yorkshire, it is best developed in the Bath district. All the Bath stones are of marine origin, and in the process of formation they were laid down by deposition in shallow seas, which were subject to many changes in current flow. On this account they vary very much in texture, and to a certain extent in colour. It is generally believed that the materials from which the Great Oolite has been derived are the waste of coral growths, and the broken-up shells of those marine creatures which swarmed in the neighbourhood of the corals. Speaking generally, the Bath stones are more open in texture than Portland stone, and somewhat coarser, and also warmer in colour, the difference in colour being accounted for, to a very large extent, by the presence of a larger quantity of ferric oxide (Fe_2O_3). The average amount of this substance in Bath stone is 1.4 per cent., whilst that in Portland stone is 0.39 per cent.

The oolite grains, or ooliths, and the shell fragments are separated by a more abundant matrix of crystalline calcite than is the case with Portland stone. The ooliths are not always perfect spheres; often their shape approaches this form, but speaking generally, their structure has been destroyed by recrystallization, so that there is considerable departure from true sphericity, some of them being almost ellipsoid. The nucleus of each oolith in almost all cases is in the form of irregular masses, often quite angular and of a crystalline nature. Many of the ooliths have nuclei composed of calcite, which under the microscope exhibits a mosaic appearance, and in some cases the nuclei are surrounded by a brown tint which is undoubtedly caused by an accumulation of ferric oxide. In other cases the nuclei are discoloured throughout, brown or reddish-brown, apparently by the same substance. Some of the nuclei are almost as large as the ooliths themselves, whilst others are very small in comparison with the whole oolith, and there are others which appear to be calcite covered with numbers of tiny grains, almost round, of a material coloured by ferric oxide.

Around the nucleus of each oolith are numbers of concentric layers of calcium carbonate which are crystalline in form. At intervals these layers are separated by zones stained brown by what seems to be oxide of iron. The number of these zones varies: in some cases five can be counted, in others seven, and yet in others ten, and the thickness of these brownish zones varies also. Many of the ooliths show indications of a radial structure of the calcite composing them, due to secondary crystallization. The ooliths and the fragmentary particles of shells are bound together by a matrix of calcium carbonate in the form of calcite, and under the microscope it appears transparent and somewhat like mosaic.

Owing to the high porosity of the Bath stones, which averages out in the neighbourhood of 10 per cent., they are, speaking broadly, not altogether suitable for use in building

thin cavity walls, or for use in the form of thin slabs as facings. It has been found in practice that walls built with thin slabs of Bath freestone, even when they are of a thickness between $4\frac{1}{2}$ and 5 inches, allowed water derived from driving rains to penetrate through them.

Combe Down Stone.—This stone when dry is of a light cream to a very light brown colour. It is medium-grained and granular in structure. Combe Down stone occasionally shows the presence of thin veins of calcite on the surface of blocks, and it is at times stained with small spots containing an abundance of oxide of iron. This stone is fairly free working, and yields a good arris and surface. The calcite veins may make working a little more difficult when they are come up against, but not to any serious extent. If it is decided to use this stone in towns and cities the atmospheres of which are polluted, then great care must be taken in its choice, and it should not be used for plinths at ground level or for enrichments.

Combe Down stone has been quarried for a great number of years at Combe Down and Odd Down, south of Bath.

Its chemical composition varies a little, average figures being as under:

Calcium carbonate (CaCO_3)	..	..	..	..	94.48
Magnesium carbonate (MgCO_3)	..	..	..	..	2.61
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	1.25
Water and loss (H_2O)	..	..	..	..	1.66

Its physical properties are given in the following table:

Specific gravity	..	..	..	..	2.04
Weight per cub. ft.	..	..	..	..	128 lbs.
Crushing resistance per sq. ft.	..	..	..	..	118 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	..	6.2

Corsham Down Stone.—When dry, Corsham Down stone is light cream in colour. In structure it is granular, or very distinctly oolitic, and moderately fine-grained; and it is regular in texture. It contains a fair amount of shell detritus, some of which is quite small in size, and there are

present also numbers of plates of calcite, most of which are very small. Patches of calcite of an appearance like fine crystalline sugar are also present. The matrix, whilst appearing chalky and non-crystalline to the naked eye, is found to be distinctly crystalline when examined under the microscope.

Corsham Down stone is moderately hard, but softer than Portland stone. It carries a sharp arris, and a fairly smooth face can be produced on it. For interior work it is a very suitable stone indeed, but for exterior work it should not be employed for enrichments and similar members. Plain ashlar, mullions, jambs, etc., and similar types of structure well above ground level can be built in this stone with more or less satisfaction. It is not one of the best stones to use in polluted atmospheres, but has given good results in many cases. This stone is quarried, or rather mined, at Corsham Down and Corsham Ridge, near Bath.

The chemical composition of this stone is approximately as follows:

Calcium carbonate (CaCO_3)	..	..	..	..	94.95
Magnesium carbonate (MgCO_3)	..	..	..	..	2.26
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	0.98
Water and loss (H_2O)	..	..	..	..	1.81

The physical properties of Corsham Down stone are as follows:

Specific gravity	..	..	..	..	2.08
Weight per cub. ft.	..	..	..	..	129 lbs.
Crushing resistance per sq. ft.	..	..	..	..	94.5 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	..	11.25

When decaying, Corsham Down stone not only exfoliates, but small pits form all over the surface; also along the lines of current bedding grooving takes place.

Monk's Park Stone.—The ground colour of this stone in the dry state is light cream, and there are markings of a very pale grey due to calcite fossils. It is markedly oolitic, the ooliths being rather less uniform in size than those in



FIG. 4.—MONK'S PARK STONE

To face p. 45

Ketton stone. Broken shell fragments occur to a small extent, and there are occasional particles of calcite crystals which glisten on a faced stone.

Monk's Park stone can be considered as fine-grained, fairly compact, and moderately hard. It carries a fair arris, and a worked face is pitted all over with comparatively tiny pits, owing to the removal, during the working of the ooliths (see Fig. 4). This stone may be used for all types of inside work, but if employed for external work it should not be used for plinths at ground level or for any carved enrichments or similar kinds of work. This stone is quarried at Corsham, near Bath.

On examination under the microscope a thin section of this stone shows a very distinctly crystalline matrix of calcite, which under a low power has a mosaic appearance; and under a high power cleavage planes can be seen. The ooliths are much further apart than is the case in Portland stone, and whilst many of them show a very marked concentric structure, in others this is entirely absent. Concentric rings in some cases are dark brown in colour. Many of the ooliths show the radial structure due to secondary crystallization. In some of them there is an irregular nucleus, which is crystalline and shows a mosaic appearance, or it is covered all over with dark brown spots. A number of the ooliths are seen to be made up of two or three smaller ooliths embedded in a finely crystalline and somewhat darker mass, and in some instances secondary crystallization of the enclosed ooliths has commenced, and appears to be penetrating into the general mass (see Figs. 5 and 6).

The chemical analysis of Monk's Park stone shows it to be a comparatively pure calcium carbonate, as will be seen from the average figures given below:

Calcium carbonate (CaCO_3)	..	..	..	..	95.56
Magnesium carbonate (MgCO_3)	..	..	..	..	0.40
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	1.52
Silica (SiO_2)	..	..	..	..	1.20
Water and loss (H_2O)	..	..	..	..	1.32

The chief physical properties are set out in the following table:

Specific gravity	..	..	..	2.20
Weight per cub. ft.	..	..	..	137 lbs.
Crushing resistance per sq. ft.	..	..	..	223.5 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	7.76

When Monk's Park stone is exposed to the weather, and decay sets in, the outside portion of the ooliths appears to suffer first from attack and is dissolved away, thus allowing, owing to reduction in size, a falling away from the matrix or an easy removal by wetting and rain. The consequence of this action is that the surface of the stone becomes rough and full of very small cavities. Although Monk's Park stone is somewhat highly porous, it puts up a very good resistance to frost, being in this case almost equal to Portland stone.

The undermentioned prices are for Monk's Park stone fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

Average type commercial building	..	12/-	per cube foot.
Fairly ornate church job	..	13/6	„ „ „

St. Aldhelm Box Ground Stone.—Dry Box Ground stone is light brown to cream in colour, and is distinctly oolitic, being somewhat coarse-grained and granular. Speaking generally, the oolitic grains are packed fairly close together, which makes this stone somewhat finer-grained than many of the other Bath stones. This stone contains a fair amount of fossil shell fragments, some of which are $\frac{1}{2}$ to 1 inch long, and its current bedding is fairly regular. A moderately good arris can be produced on this stone, and a worked face has a somewhat granular appearance. It can be used quite satisfactorily for mouldings, cornices, string courses, sills, etc., and has been employed by some architects for carved

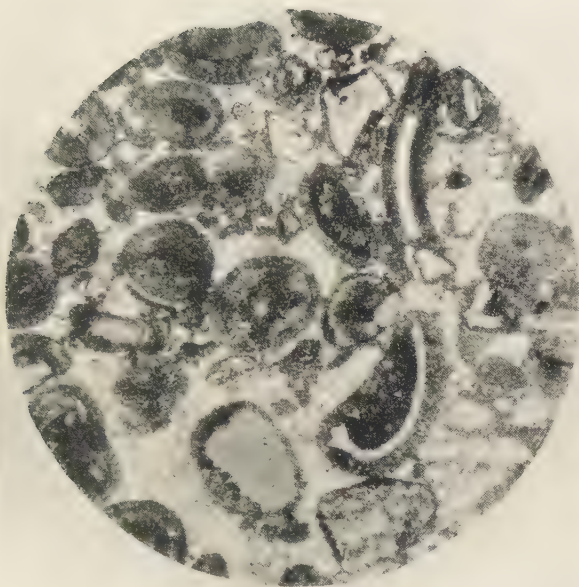


FIG. 5.—MONK'S PARK STONE
Section magnified 30 diameters. Note mosaic appearance of
calcite binding material

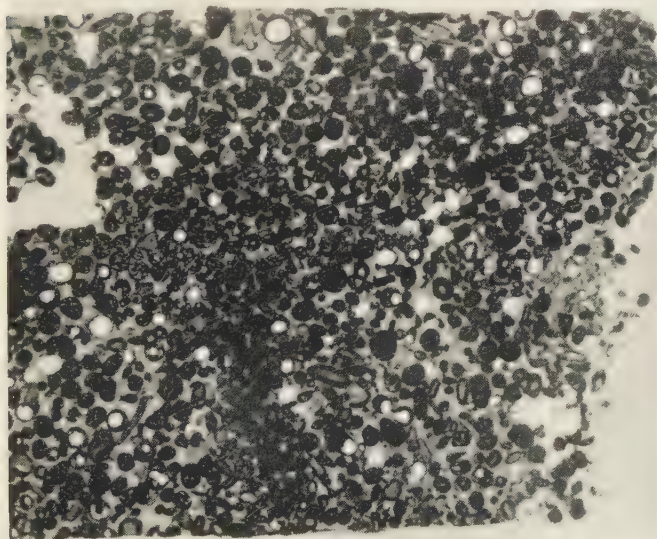


FIG. 6.—MONK'S PARK STONE
Section magnification 5. The lighter patches are calcite
To face p. 46

work. This stone weathers very well in most positions, and may be considered as one of the best, if not the best, of the Bath stones. It is obtained from the Box Ground Quarries, near Bath.

A microscopical examination of a thin section of this stone shows that the ooliths and shell fragments are, compared with Portland stone, fairly far apart. The ooliths are of various sizes and shapes, and some of them have as a nucleus broken shell fragments, whilst others have a mass of crystalline calcite. Both the concentric and radial structures can be seen in the ooliths, and many of them are stained with oxide of iron. The matrix is calcium carbonate in the form of calcite, and has a mosaic appearance.

The chemical composition of this stone is shown in the following table:

Calcium carbonate (CaCO_3)	..	..	..	..	94.32
Magnesium carbonate (MgCO_3)	..	..	..	..	2.40
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	1.51
Water and loss (H_2O)	..	..	..	..	1.77

The chief physical properties are as under:

Specific gravity	..	..	..	2.09
Weight per cub. ft.	..	..	..	129 lbs.
Crushing resistance per sq. ft.	..	..	..	107 tons (Rivington)
Absorption, per cent. of its dry weight	..	..	..	7.90

This stone is fairly resistant to decay, even in polluted atmospheres, and it is, practically speaking, unaffected by frost. The weathering is often strikingly uniform over the whole surface, and the fossils will stand out in relief. In some instances this stone appears to weather back variously according to its position in a building. Cills and weatherings will become eroded to a depth between $\frac{1}{32}$ and $\frac{3}{16}$ inch in certain positions, and in other positions the erosion will have extended to a depth of $\frac{1}{4}$ inch, all in the same period of time.

The undermentioned approximate prices are for St. Aldhelm Box Ground stone fixed complete, including the cost of scaffolding, based on large works, and calculated at the

time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

Average type commercial building	..	12/-	per cube foot.
Fairly ornate church job		13/6	„ „ „

Farleigh Down Stone.—When dry this stone is a warm cream colour, and it is distinctly oolitic, has a fine grain, and is even in texture. Although not suitable for outside work, for all kinds of interior work it is quite satisfactory, and it can be used for fine carving. It does not weather at all well, especially if exposed to polluted atmospheres. This stone is quarried at Monkton Farleigh.

Its physical properties are:

Specific gravity		1.95
Weight per cub. ft.		121 lbs.
Crushing resistance per sq. ft.		62 tons (Beare)
Absorption, per cent. of its dry weight	..	13.5

Hartham Park Stone.—When dry this stone is warm cream to yellow in colour, it is fine-grained, and possesses an even texture. It takes on a good arris, gives a comparatively smooth face, and if carefully chosen and fixed on its natural bed it may be employed with satisfactory results in all atmospheres but those which are very polluted. This stone is quarried, or rather mined, at Upper Pickwick, near Hartham Park.

Its physical properties are:

Specific gravity		2.17
Weight per cub. ft.		135 lbs.
Crushing resistance per sq. ft.		123.5 tons.
Absorption, per cent. of its dry weight	..	11.6

Stoke Ground Stone.—In the dry state Stoke Ground stone is a light brown colour, and it is distinctly oolitic, medium-grained, and somewhat open in texture. It yields a fair arris and a moderately smooth surface, and can be employed for some types of carved work. This stone weathers very well in most atmospheres (highly polluted atmospheres

excepted), but it is not advisable to use it for plinths at ground level. It is quarried at Limpley Stoke.

Its physical properties are:

Specific gravity	2.03
Weight per cub. ft.	127 lbs.
Crushing resistance per sq. ft.	107 tons (Beare)
Absorption, per cent. of its dry weight ..	10.8

Beer Stone.—In the dry condition this stone is almost white; many persons consider it a pale cream colour. It occurs in the basement beds of the Middle Chalk of the Cretaceous system. In texture it is fine-grained and compact, but it is soft and easily rubs up chalky. It contains a fairly large quantity of very small calcite plates, which are only obvious on a fresh fractured surface, and also a small quantity of shell fragments, some of which are about $\frac{1}{4}$ inch across. Scattered sparingly throughout its mass are small particles of glauconite, and also siliceous matter in the form of sponge spicules and colloidal granules. The bulk of this stone is made up of foraminifera and echinoderm plates embedded in a matrix of calcium carbonate in the form of calcite. Under a hand-glass Beer stone appears to be very crystalline, whilst to the naked eye it seems practically non-crystalline. In this stone there is a small quantity of earthy or argillaceous matter, the amount of which varies between 1.8 and 3.5 per cent.

Beer stone takes a moderately sharp arris, and works to a smooth face. Its soft nature lends itself to fine carved work, but renders it unsuitable for exterior work. To employ this stone in manufacturing cities or towns, the atmospheres of which are polluted, is unwise.

In regard to its chemical composition, Beer stone may be considered as technically pure calcium carbonate. It is quarried at the Beer Quarries, Seaton, Devonshire.

Its chief physical properties are:

Specific gravity	2.12
Weight per cub. ft.	132 lbs.
Crushing resistance per sq. ft.	152 tons.
Absorption, per cent. of its dry weight ..	12.15

Beer stone decays comparatively rapidly in polluted atmospheres, and the usual form exhibited is that of ex-foliation with more or less small scabby laminæ.

Blaxter Stone.—This stone is a Millstone grit of the Carboniferous system, and is quarried near Newcastle. It is of a light buff colour, close-grained, and contains glistening specks of white mica (muscovite). The sand grains are chiefly silica bound, the subsidiary binding materials being iron and aluminium oxides. It is quite free of the carbonates of the alkaline earths, such as calcium or magnesium carbonates.

Blaxter stone is moderately absorptive of water, takes on a comparatively smooth surface, and works to a good arris. It is a somewhat soft stone; a tooled surface can be disintegrated to a small degree by scratching with the finger nails, or even if rubbed with the fingers.

This stone is not used to any very great extent. It is employed locally, and recently has been used in the facings and dressings of the elevations of the Armstrong College Library, Newcastle.

Bolsover Moor Stone.—This stone is a dolomite or magnesian limestone, and when dry is warm yellowish-brown in colour. Like Anston stone it was formed in the large inland seas of the Middle Permian series of the Permian system, and in all probability by the process of metasomatism. The current bedding is generally irregular and oblique, and the stone is very fine-grained and compact. It is crystalline in structure owing to the fact that it consists very largely of dolomite rhombs. These are rather larger than those in Anston stone, and they contain less of the dull colouring matter (oxide of iron). Sparsely scattered throughout this stone are angular grains of quartz, and the appearance of a fresh fracture is somewhat crystalline. Bolsover Moor stone is similar to Mansfield Woodhouse stone, both in appearance and texture. It takes a very good arris, works up to a smooth face, and is suitable for carved work. Owing to the smallness of the blocks which

are quarried, its use is restricted; Mansfield Woodhouse is often substituted for this stone.

This stone weathers well in most atmospheres, but it should be used with caution, or not at all, in London. Care must be taken when fixing to place it on its natural bed. It is quarried at the Bolsover Moor Quarries in Derbyshire.

The approximate chemical composition of Bolsover Moor stone is:

Calcium carbonate (CaCO_3)	..	..	..	..	51.6
Magnesium carbonate (MgCO_3)	..	..	..	..	40.8
Silica (SiO_2)	..	..	..	..	3.2
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	2.1
Water and loss (H_2O)	..	..	..	..	2.3

The chief physical properties of this stone are as under:

Specific gravity	..	..	..	2.44
Weight per cub. ft.	..	..	..	152 lbs. (Rivington)
Crushing resistance per sq. ft.	..	..	..	484 tons (Royal Com.)
Absorption, per cent. of its dry weight	..	..	..	8.2

When Bolsover Moor stone decays the chief form exhibited is that of exfoliation, which is produced by a growth of crystals of magnesium and calcium sulphate along the lines of current bedding; this kind of decay is similar to that of Anston stone.

Bramley Fall Stone.—In the dry state this stone is light brown in colour, and mottled with rather deeper spots. It is a coarse-grained sandstone of the Millstone Grit series, of the Carboniferous system. The sand of this stone consists chiefly of quartz, and it contains some felspar, whilst the matrix or binding material is silica. It is most probable that the origin of the sand grains is granite. Whilst this stone is hard and durable, its coarseness limits its use for architectural work, especially for enrichments. It does not take a fine arris, and when surfaced is far from smooth, but for heavy engineering structures it is largely employed. This stone is quarried at the Horsforth Quarries, near Leeds.

There is a drab, fine-grained Bramley Fall stone quarried

at the Pool Bank Quarries, near Otley, Yorkshire, which is much more suitable for architectural and ornamental purposes. It is a hard stone, and somewhat difficult to work.

The approximate chemical composition of the Horsforth quality is as under:

Silica (SiO_2)	..	..	..	..	..	96.58
Aluminium oxide (Al_2O_3)	..	..	..	..	..	1.10
Iron oxide (Fe_2O_3)	..	..	..	..	..	0.34
Magnesium and calcium oxides (MgO and CaO)	..	..	..	..	..	0.49
Water and loss (H_2O)	..	..	..	..	..	1.49

(Fairley)

and the composition of the Pool Bank quality is very similar.

The stone from the Horsforth Quarries possesses the following physical properties:

Specific gravity	..	..	..	..	2.63
Weight per cub. ft.	..	..	..	..	163 lbs.
Crushing resistance per sq. ft.	..	..	..	..	552.2 tons.
Absorption, per cent. of its dry weight	..	..	..	..	3.9

and that from the Pool Bank Quarries:

Specific gravity	..	..	..	..	2.28
Weight per cub. ft.	..	..	..	..	142 lbs.
Crushing resistance per sq. ft.	..	..	..	..	238 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	..	3.68

Bramley Fall stone possesses excellent weathering properties in all atmospheres. The chief source of decay is the growth of crystals from salts leached out of the mortar used in fixing or pointing. The forms of decay most seen are those of exfoliation in small flakes, or pitting, due to the separation of the sand grains brought about by the breaking away of the silica matrix or binding material.

Blue Bristol Pennant Stone.—This stone is dark blue-grey in colour, is fine-grained and hard, and it occurs in the Coal Measures series of the Carboniferous system. It contains a fair amount of small flakes of mica, and some small black specks, both of which are obvious on a smooth face. The matrix which binds the sand grains together consists of

silica supplemented by calcium carbonate and iron and aluminium oxides. A good arris and face can be formed on this stone, and it is suitable for interior and exterior work, whether in plain ashlar, moulded work, or sculptured work. In most atmospheres it is durable, but in the polluted atmospheres of manufacturing towns and cities it is liable to some decay. It is quarried at the Fish Pond Quarries, near Bristol.

The approximate chemical composition of Blue Pennant stone is as under:

Silica (SiO_2)	..	..	..	..	..	73.93
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	..	13.87
Calcium carbonate (CaCO_3)	..	..	..	..	..	3.64
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	6.71
Water and loss (H_2O)	..	..	..	..	..	1.85

Its chief physical properties are given below:

Specific gravity	..	..	..	2.76
Weight per cub. ft.	..	..	..	172 lbs.
Crushing resistance per sq. ft.	..	..	..	1,001 tons (Kirkaldy).
Absorption, per cent. of its dry weight	..	..	..	3.4 to 4.5

Caen Stone.—This is a French stone which in the past was largely used in this country, especially in the South, and even to-day it is employed a little. It resembles to an extent the British Oolites, and it occurs in the Great or Bath Oolite series of the Jurassic system. When dry it is pale cream or yellowish-white in colour. In structure it is very fine-grained, but shows practically no indication of oolitic structure, and owing to the method by which it was formed geologically it is liable to some variation in quality.

A good arris and a smooth face can be produced on it, and on account of its fine texture it is eminently suitable for carved work. Unfortunately it is very liable to attack by polluted atmospheres and rain, and this excludes its use entirely for outside work. For interior work it is suitable, but even in this case it is apt to suffer, especially in large buildings into which foggy or other polluted atmospheres

may enter, or if the buildings are gas-lighted or heated by coke fires placed in wrong positions.

It is quarried near Caen in the Calvados Province of France.

Its chemical composition is very close to that of the Bath stones, containing approximately 95 per cent. of calcium carbonate.

Its chief physical properties are as under:

Specific gravity	..	..	..	2.70
Weight per cub. ft.	..	..	..	168 lbs.
Crushing resistance per sq. ft.			..	198 tons (Rivington)
Absorption, per cent. of its dry weight				11.2

The characteristic form of decay in the case of this stone is exfoliation; the scales or scabs are not as a rule very large or thick, and they form on top of each other, more or less, giving the decaying surface a rippled appearance. Often in mouldings and other enrichments bursting takes place along a line of current bedding, and the exfoliated portions in these circumstances are often very thick. After a number of years' exposure to the weather and polluted atmospheres, the substance of this stone to some depth below the surface becomes very soft and can be easily rubbed to a powder.

Caithness Stone.—This stone is dark blue-grey in colour, moderately fine-grained, compact, and tough. It is quarried out of the Old Red Sandstone deposits of the Devonian system, and, strictly speaking, is a bitumino-calcareous sandstone. The sand contained in it is a mixture chiefly composed of quartz and felspar grains, and these are bound together by a matrix of silica, calcium carbonate, and bituminous matter. It is the presence of bitumen which adds much to its durable qualities.

Whilst it is employed locally for general building purposes, it finds its chief use for flagstones, steps, and landings, and for these purposes it has been used all over the world.

There seems to be a lack of information as to its behaviour

in polluted atmospheres, and careful tests should be made before deciding to employ it in general building work in cities or towns on account of the large proportion of calcium carbonate contained in it. This stone is quarried from the Castle Hill Quarries, Thurso, Caithness-shire.

Its approximate chemical composition is:

Silica (SiO_2)	..	..	..	..	..	69.50
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	..	10.50
Calcium carbonate (CaCO_3)	..	..	..	..	..	10.65
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	2.20
Bituminous matter	..	..	..	..	..	5.79

The chief physical properties of this stone are:

Specific gravity	..	..	..	..	..	2.52
Weight per cub. ft.	..	..	..	..	..	157 lbs.

Chilmark Stone.—This stone occurs in the Upper Oolite series of the Jurassic system. In colour it varies somewhat between buff and yellowish-brown, and it is distinctly siliceous, the silica occurring partly in the form of sand grains, partly as glauconite (a complex silicate of potassium, aluminium, and iron), and partly as a siliceous cement. The greenish tint which develops in all Chilmark stone after it has weathered is due to the mineral glauconite.

The Chilmark deposits may be divided up into three chief beds—viz., the Trough bed, the Green bed, and the Pinney bed.

Trough Bed.—This is a buff to yellowish-brown stone, more or less oolitic in structure, and it can be considered as sandy. It is hard, and usually weathers the best of all the types of Chilmark. For general building purposes it may be used for plain ashlar, cornices, plinths, cills, etc., and it is also suitable for steps and paving.

Green Bed.—The stone from this bed is either buff or pale greenish-grey in colour. In structure it varies somewhat: it is glauconitic and sandy, and at times shelly. It is a hard stone which weathers well, and it may be used for mouldings, cornices, carved work, plain ashlar, etc.

Pinney Bed.—This stone is brownish in colour, more or less oolitic in structure, and is also glauconitic and sandy, and is more obviously crystalline than the stone from the other two beds. In general building work it can be used for practically all purposes, but it is liable to weather badly in the polluted atmospheres of manufacturing towns or cities.

The approximate chemical composition of the Chilmark stones is:

Calcium carbonate (CaCO_3)	..	..	..	78.80
Magnesium carbonate (MgCO_3)	..	..	..	3.90
Silica (SiO_2)	..	..	..	10.34
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	2.51
Water and loss (H_2O)	..	..	..	4.45

The chief physical properties are:

Specific gravity	..	..	..	2.48
Weight per cub. ft.	..	..	..	154 lbs.
Crushing resistance per sq. ft.	..	..	..	136.6 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	7.5 to 8.0

When Chilmark stone decays, one of the usual forms presented is that of scabbing, and very often the entire surface of a block of stone becomes covered with scabs. The exfoliated portions vary in thickness, the average being about $\frac{1}{16}$ inch. On mouldings and other enrichments exfoliation often occurs along the lines of current bedding, and the splitting may commence at a depth of $\frac{3}{4}$ inch or more from the surface.

The first visible indication of decay is, in a large number of cases, the appearance of blisters, and if the cover of one of these blisters is removed carefully it will often expose bunches of very fine white crystals, which on chemical examination prove to be chiefly calcium sulphate. Sometimes the decay becomes more marked along the lines of current bedding, or between layers of fossils, producing a peculiar furrowed effect.

Clipsham Stone.—Like Ancaster stone, Clipsham stone is a member of the Lincolnshire Limestone deposits. These deposits occur in the Inferior Oolite of the Jurassic system,

and as the material from which this stone was formed was probably deposited in a moderately shallow sub-tropical sea, in which changes in the direction of currents were more or less frequent, its quality is liable to a certain amount of variation. When dry, the colour of Clipsham stone may vary between pale cream and buff.

The ground colour of the stone from the Old Quarry, near Oakham, is buff, and there are small spots or patches of a light brown colour. It is coarse-grained and somewhat oolitic, and among the clastic are very small pebbles and large numbers of shell fragments. Throughout the whole mass of the stone are large numbers of plates of calcite, which give it a peculiar glistening appearance. The matrix under an ordinary hand lens has an earthy appearance, but if examined by the microscope it is found to be crystalline; it consists of calcite.

The stone from the Big Pits Quarry, Clipsham, is pale cream in colour, medium-grained, and very distinctly oolitic. The ooliths are of a variety of shapes, and there are also in this stone numbers of shell fragments and some very small pebbles. Among the shell fragments are portions of encrinites and echinoderms. Scattered in the mass of the stone are numbers of glistening crystals of calcite, and the whole of the clastic is bound together by a matrix of the same material. On a faced surface of this stone a great number of the fragmentary particles appear somewhat greyish and opaque.

This stone has been, and is still, largely employed for general building work; it is most suitable for plain ashlar and ordinary members, such as copings, moulded stringers, cornices, etc., but has been used with a very fair amount of success for carved work.

Its approximate chemical composition is as under:

Calcium carbonate (CaCO_3)	..	..	..	..	97.56
Magnesium oxide (MgO)	..	..	..	..	0.54
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	0.83
Insoluble residue (chiefly SiO_2)	..	..	..	..	0.84
Water and loss (H_2O)	..	..	..	..	0.23

Its chief physical properties are:

Specific gravity	..	..	..	2.42
Weight per cub. ft.	..	..	..	150 lbs.
Crushing resistance per sq. ft.	..	..	..	291.6 tons (Kirkaldy)

The undermentioned approximate prices are for Clipsham stone fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

Average type commercial building	..	19/-	per cube foot.
Fairly ornate church job	..	23/-	„ „ „

Closeburn Stone.—This stone occurs in the Triassic system. It varies in colour between light and dark red, and both colours are fine-grained and slightly micaceous, with obvious current bedding. It is an almost pure sandstone, the sand grains of which are silica-bound. Among the sand grains, which are chiefly quartz, are to be found fragments of felspar. For general building work it is a suitable stone, taking a fairly good arris and working to a comparatively smooth surface. Closeburn stone is quarried near Thornhill, Dumfriesshire.

The approximate chemical composition is given under:

Silica (SiO_2)	..	..	..	91.76
Aluminium oxide (Al_2O_3)	..	..	..	4.48
Ferric oxide (Fe_2O_3)	..	..	..	0.95
Ferrous oxide (FeO)	..	..	..	0.06
Magnesium oxide (MgO)	..	..	..	0.18
Calcium oxide (CaO)	..	..	..	0.27
Potassium oxide (K_2O)	..	..	..	1.40
Sodium oxide (Na_2O)	..	..	..	trace
Loss	..	..	..	0.90

Its chief physical properties are:

Specific gravity	..	..	..	1.98
Weight per cub. ft.	..	..	..	123.5 lbs.
Crushing resistance per sq. ft.	..	..	..	478 tons (Beare)

Clunch Stone.—The deposits in the Lower Chalk series of the Cretaceous period yield beds of rather hard chalk, which are known under the generic name of Clunch. Strictly speaking, true Clunch consists of the harder bands occurring in the Chalk Marl of Cambridgeshire. This Chalk stone varies in colour from white to greenish-grey, the latter colour being due, to a very large extent, to small grains of glauconite which are scattered throughout its mass. The greenish-grey Clunch has a granular appearance, and this is due to the fact that the greater part of the rock is composed of minute polygonal cylinders of calcite, the result of the breaking down of the large oyster-like shells of *Inoceramus*. The matrix which binds these crystals is calcareous and somewhat muddy (argillaceous). In texture Clunch stone is compact and fine-grained, and on weathering it is liable to develop reddish-like patches, due to the decomposition of glauconite with the formation of ferric oxide.

Totternhoe stone is classified by some as a Clunch stone. This stone is also of the Lower Chalk, and the deposits from which it is obtained overlie the Chalk Marl. It is a greenish-white, fine-grained stone, the unfaced surface of which feels rough to the touch, and on account of this it has been called an arenaceous chalk. The cause of this rough surface is the presence of a large quantity of calcite prisms and sand grains. The matrix of this stone is calcareous and chiefly calcite, which is crystalline in structure. This stone occasionally contains tiny nodules of iron pyrites, and these when exposed to the atmosphere become oxidized, not only producing red stains but assisting in causing disintegration of the stone, owing to the formation of ferrous and ferric sulphates, and probably traces of sulphuric acid.

The Chalk stones are quite unsuitable for exterior work, although from time to time they have been used in this connection, especially in districts in proximity to the quarries. For interior work they may be used, provided they do not come in contact with polluted atmospheres, either due to lighting or heating or the situation of the

building in a manufacturing centre. They are easy to work and carve, and they are not as a rule difficult to quarry, and on this account the temptation exists to use them for general building purposes.

The chemical composition of the Chalk stones varies considerably; the chief constituent is calcium carbonate, and there is present also aluminium silicate and iron oxide, and often small quantities of silica.

The chief physical properties are as under:

TRUE CLUNCH.

Specific gravity	..	..	..	..	..	2.13
Weight per cub. ft.	..	..	..	..	..	133 lbs.
Crushing resistance per sq. ft.	..	..	..	..	..	72 tons

TOTTERNHOE STONE.

Specific gravity	..	..	..	1.86
Weight per cub. ft.	..	..	..	166 lbs.
Crushing resistance per sq. ft.	..	..	..	124 tons (Rivington)

The usual form taken up by the Chalk stones when they decay is that of exfoliation, the scabs or laminae forming one on top of the other. Blocks of this stone will erode back very quickly into deep cavities, often almost as large in area as the face of the block itself. These stones are very liable to become affected by the action of frost, and when this does occur, exfoliation is increased.

Cotswold Dale Stone.—This stone occurs in the Inferior Oolite deposits of the Jurassic system. When dry it is rich cream in colour, speckled with very light brown spots, together with occasional spots of a dark brown colour. In structure it is medium-grained, and it is distinctly oolitic (see Fig. 7). It contains a very small amount of shelly detritus, and a few plates of calcite. The matrix consists of calcium carbonate in the form of calcite which, when seen under the microscope, is distinctly crystalline. This stone is moderately hard, yields a fairly good arris, and it works up to a more or less smooth surface, which is filled



FIG. 7.—COTSWOLD DALE STONE

To face p. 60

with tiny cavities due to the removal of the ooliths during the process of preparation. It should be noted that individual blocks of this stone are liable to variation.

This stone is quarried in the Leckhampton Quarries, Gloucestershire.

Corsehill Stone.—This stone occurs in the New Red Sandstone deposits of the Jurassic system. It is a fine-grained, very compact, even textured, and slightly micaceous sandstone, the colour of which varies between bright pink and dark red, that most used being of a warm red shade. Current bedding can be seen in some blocks of this stone, especially if closely examined. The sand grains of this stone consist chiefly of quartz and felspar, with a small quantity of zircon and other minerals, the whole being cemented together chiefly by silica, magnesium and calcium carbonates and oxide of iron acting as subsidiary binders. It can be considered as a moderately porous stone, being somewhat similar in this respect to Portland stone.

A microscopical examination of a thin section of Corsehill stone shows that the sand grains are very small, some of them being angular, but the majority subangular in shape. They are packed very closely together, and the surfaces of most of the grains appear to be covered with a thin layer or pellicle, which is reddish-brown in colour. There are also occasional patches of material of the same colour, which are almost as large as the sand grains, and these appear to be made up of very small sand grains cemented together chiefly by oxide of iron (see Figs. 8 and 9).

A good arris and a smooth face can be prepared on this stone, and it can be sculptured. It is a very good stone for use in plain ashlar, but practical experience has shown that when used in carvings, mouldings, and projections, and particularly in cornices, it is liable to laminate, with the result that in time pieces fall off. In polluted atmospheres the exposed face of the stone shows a tendency to "bleach." This stone is quarried at Annan, Dumfriesshire.

The approximate chemical composition of this stone is given below:

Silica (SiO_2)	..	..	..	..	95.33
Aluminium oxide (Al_2O_3)	..	..	..	..	0.59
Ferric oxide (Fe_2O_3)	..	..	..	..	1.28
Calcium carbonate (CaCO_3)	..	..	..	..	1.49
Magnesium carbonate (MgCO_3)	..	..	..	..	1.31

If a chip of Corsehill stone is placed in a cold diluted aqueous solution of hydrochloric acid (1:1), vigorous effervescence takes place which lasts for several minutes: this is due to the acid attacking the calcium and magnesium carbonates. On boiling a chip of this stone in the same strength of acid a certain amount of disintegration takes place, indicated by the presence of some sand grains at the bottom of the reaction vessel. After washing with water the acid-treated stone is nearly white, and the sand grains on the surface are very much looser than before the treatment.

A microscopical examination of an acid-extracted chip shows that the sand grains are still cemented together by silica, but the mass is more cellular than an unextracted piece, due to the removal of the subsidiary cementing materials, calcium and magnesium carbonates, and oxide of iron. It should be noted that the strength of the stone is much weakened by the action of this acid.

The chief physical properties of Corsehill stone are:

Specific gravity	..	..	..	2.26
Weight per cub. ft.	..	..	..	141 lbs.
Crushing resistance per sq. ft.	..	..	..	635 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	6.25

This stone when decaying generally exfoliates, the splitting taking place as a rule along the lines of current bedding. The thickness of the scales or scabs may vary from approximately $\frac{1}{16}$ to 1 inch, and even more. Accompanying this form of decay is that of eroding along the lines of current bedding eventually forming furrows.

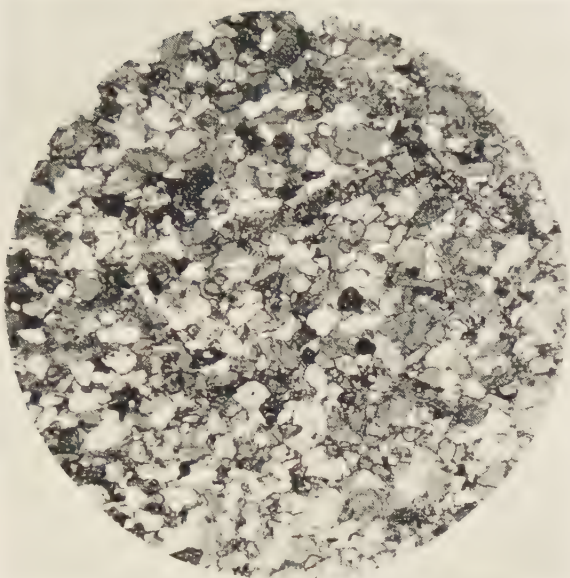


FIG. 8.—CORSEHILL STONE
Section magnified 30 diameters



FIG. 9.—CORSEHILL STONE
Section magnification 5

Craigleith Stone.—Craigleith stone is a slightly calciferous sandstone which occurs in the Carboniferous series. When dry the colour of this stone is whitish-grey or drab, it is very slightly micaceous, and its texture is fine-grained. The chief constituent of this stone is quartz sand, and the matrix is composed mainly of silica, the subsidiary binder being calcium carbonate, which occurs in small quantity. Craigleith stone has been used for many years for building purposes, especially in Scotland, and the original quarries are now practically exhausted. As a substitute Hailes stone is being used, and this stone in most of its properties runs very close to the original Craigleith stone. A sharp arris and a smooth face can be prepared on this stone, and it has proved itself quite suitable for all general building purposes, and also for sculptural work.

Its average chemical composition is:

Silica (SiO_2)	..	..	..	..	..	97.62
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	..	1.45
Calcium carbonate (CaCO_3)	..	..	..	..	..	0.65
Water and loss (H_2O)	..	..	..	..	..	0.28

The chief physical properties are as under:

Specific gravity	..	..	..	2.22
Weight per cub. ft.	..	..	..	138 lbs.
Crushing resistance per sq. ft.	..	..	..	802 tons (Rivington)
Absorption, per cent. of its dry weight	..	..	..	3.6

Darley Dale Stone.—This stone occurs in the Millstone Grit series of the Carboniferous system. When dry the colour of this stone may vary between a very light buff colour and a light grey. In the case of the latter the surface is speckled with a quantity of darker grey spots, which give it a “pepper-and-salt” appearance, and a small amount of white mica is to be seen. The matrix which binds the sand grains together is chiefly silica, and the sand grains themselves are mainly particles of quartz, there being a small quantity of fragments of felspar. The stone is fine-grained, and it takes a good arris, and a prepared surface is moderately smooth.

The buff-coloured stone is speckled with spots of very light grey, and occasionally some of reddish-brown due to a local accumulation of oxide of iron, and a small amount of mica is present. It is a fine-grained hard sandstone, a prepared surface of which is smoother than that of the grey type. Like the grey stone the matrix or natural cement is silica, and to a very large extent this matrix is formed by secondary crystallization after the sand grains have been deposited. The texture of this stone is liable to vary a little, and some blocks may be considered as medium-grained. This stone is quarried at the Peasenhurst Quarries, and the Stancliffe Quarries, Derbyshire.

The approximate chemical composition of the Darley Dale stones is given under:

Silica (SiO_2)	..	..	..	..	..	95.98
Calcium carbonate (CaCO_3)	..	..	..	..	..	0.29
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..	..	..	..	..	1.93
Water and loss (H_2O)	..	..	..	..	..	1.80

The chief physical properties are as under:

LIGHT BUFF STONE.

Specific gravity	..	..	..	2.46
Weight per cub. ft.	..	..	..	153 lbs.
Crushing resistance per sq. ft.	..	..	..	455 tons (Rivington)
Absorption, per cent. of its dry weight	..	..	..	3.5

LIGHT GREY STONE.

Specific gravity	..	..	..	2.38
Weight per cub. ft.	..	..	..	148 lbs.
Crushing resistance per sq. ft.	..	..	..	670.3 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	3 to 4

The Darley Dale stones weather splendidly in all parts of Great Britain, and, provided it is properly fixed, it suffers very little from general decay. Like practically all sandstones, if it is exposed to the smoky atmospheres of big cities it becomes very dirty, owing to the soot and grime being held somewhat tenaciously by the slightly rough



FIG. 10.—DOULTING STONE (BRAMBLEDITCH
OR FINE BED)



FIG. 11.—DOULTING STONE (CHELYNCH BED)

To face p. 65

surface, and the removal of this dirt often presents a difficult proposition.

The undermentioned approximate prices are for Darley Dale stone fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

Average type commercial building	..	21/6	per	cube	foot.
Fairly ornate church job	..	26/-	„	„	„

Douling Stone.—This stone occurs in the Inferior Oolite of the Jurassic system. It is of a shallow water origin, the material of which it is composed being laid down in warm seas composed of clear water. The bulk of this stone is made up of fragments of crinoids (*Pentacrinus*, etc.), and of several types of shells, the whole of which is bound together by a matrix of crystalline calcite. It is sparingly oolitic in structure, and is slightly siliciferous, and on exposure the surface sometimes develops a glassy skin.

There are two chief varieties of this stone: the Brambleditch or fine-bed, and the Chelynych or grey-bed. The Brambleditch stone (see Fig. 10) when dry is a rich cream colour, with patches of light grey, due to fragmentary material, and on a prepared surface these patches present a glistening appearance. It is a fine-grained crystalline limestone, the faced surface of which is somewhat smoother than one prepared on the Chelynych bed stone, and it takes on a rather ragged arris. It is not suitable for general building work, but can be used for the construction of interiors.

The Chelynych bed stone (see Fig. 11) is pale buff in colour, and is speckled with light grey, more or less in patches. These patches are due to fragments of fossils, and on a prepared surface they present a somewhat shiny and glistening appearance. The fragmentary material is coarse, the greater part of it obviously crystalline, and it is cemented

together by a buff-coloured matrix. This stone can be considered as coarse-grained, and yet compact. It does not give a sharp arris, and a faced surface is somewhat pitted owing to portions of the clastic being dragged out during preparation. For general building work in unpolluted atmospheres it behaves very satisfactorily, but it cannot be considered suitable for use in London or other cities possessing impure atmospheres.

A microscopical examination of Doultong stone (Chelynych) shows that it is very slightly oolitic, the clastic consisting chiefly of broken shell fragments, pieces of crinoids, and echinoderm plates (see Figs. 12 and 13). The whole mass is distinctly crystalline, the matrix having a mosaic appearance, and much of the fragmentary matter is coloured brown, to different depths of shade, due to oxide of iron. This stone is quarried at the St. Andrew's Quarries, near Shepton Mallet, Somersetshire.

The approximate chemical composition of the Doultong stones is as under:

Calcium carbonate (CaCO_3)	..	..	95.83
Aluminium oxide (Al_2O_3)	..	..	0.91
Iron oxide (Fe_2O_3)	..	..	0.78
Silica (SiO_2)	..	..	1.96
Water and loss (H_2O)	..	..	0.52

There is a difference in the physical properties of the Brambleditch and the Chelynych stones which will be seen on reference to the table below:

	<i>Specific gravity.</i>	<i>Weight per cub. ft. in lbs.</i>	<i>Crushing resistance per sq. ft.</i>	<i>Absorption, per cent. of its dry weight.</i>
Brambleditch ..	2.01	125	104	10.5
Chelynych ..	2.41	150	211.6	3.4

The two chief forms of decay exhibited by this stone are that of exfoliation or scabbing and pitting. There is a

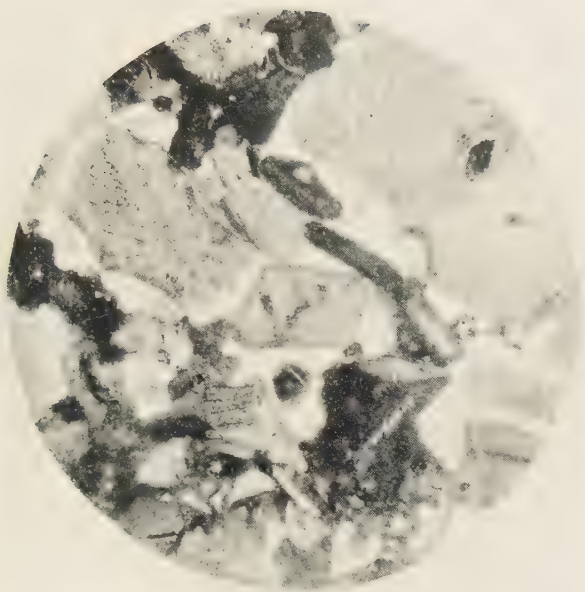


FIG. 12.—DOULTING STONE (CHELYNCH BED)
Section magnified 30 diameters. Note broken shell fragments

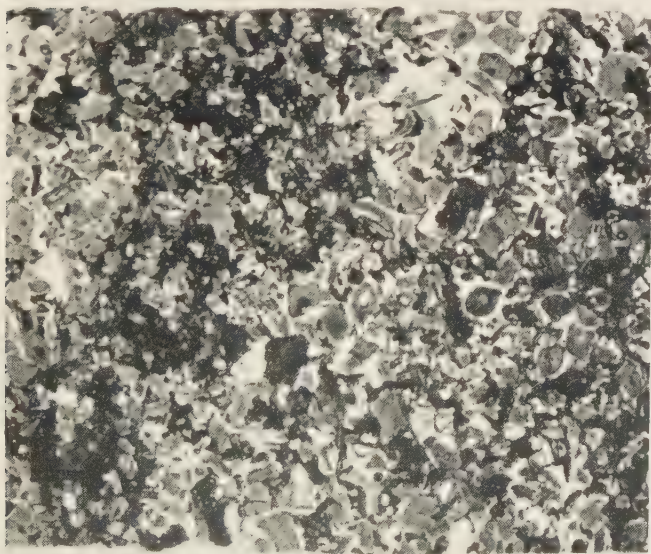


FIG. 13.—DOULTING STONE (CHELYNCH BED)
Section magnification 5. The very light patches are the calcite of the
matrix

variation in the size of the scales formed during exfoliation from very small to comparatively large, and in thickness from $\frac{1}{16}$ to $1\frac{1}{2}$ inches, and even more at times. Weatherings which are very much exposed often develop a deep troughing or furrowing along the lines of current bedding, as well as a deep pitting over most of the surface. The face of a pitted stone often becomes so friable that it can be easily disintegrated by rubbing with the fingers. Arrises and drip edges, etc., crumble away and pieces fall off, producing a very ragged appearance. Buildings in London erected in this stone between twenty-five and thirty years ago, to-day show bad decay.

Forest-of-Dean Stone.—This stone occurs in the Pennant Grit deposits of the Coal Measures series of the Carboniferous system. There are two qualities, a Blue and a Grey, and they are fine-grained, slightly calcareous sandstones containing a small quantity of mica (muscovite). The sand grains are mainly quartz, with some orthoclase felspar, and they are bound together chiefly by silica, the subsidiary cements being calcium and magnesium carbonates, calcium sulphate, and iron oxide; many of the grains are covered by a thin pellicle of the last-named material. If a thin section of this stone is examined under the microscope (see Figs. 14 and 15) it will be seen that the structure is very compact, the sand grains are mainly sub-angular and are small, and there are numerous light brown patches interspersed throughout the mass. Also, quite a large quantity of accumulations of very tiny sub-angular particles become visible.

The Blue variety is dark blue-grey in colour, hard, and a little more compact than the Grey quality, free from tiny cavities, and among the sand grains small particles of slaty rock are to be seen. This stone takes on a sharp arris, and a faced surface is smoother than can be obtained on the Grey stone.

The approximate chemical composition of Blue Forest-of-Dean stone is given as follows:

Silica (SiO_2)	..	..	..	..	79.19
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	15.95
Calcium carbonate (CaCO_3)	..	..	..	..	3.13
Magnesium carbonate (MgCO_3)	..	..	..	..	0.31
Calcium sulphate (CaSO_4)	..	..	..	..	0.92
Water and loss (H_2O)	..	..	..	..	0.50

Its chief physical properties are:

Specific gravity	..	..	..	2.44
Weight per cub. ft.	..	..	..	152 lbs.
Crushing resistance per sq. ft.	..	..	..	631 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	2.82

Grey Forest-of-Dean stone (see Fig. 15*a*) is drab grey in colour, fine-grained, contains a moderate amount of small flakes of mica and a quantity of tiny dark grey spots. On a fractured surface indications of flaking can be seen. It is a hard stone upon which can be worked a sharp arris and a smooth surface; the latter, when closely examined, is found to be full of tiny cavities.

Its approximate chemical composition is given under:

Silica (SiO_2)	..	..	..	..	80.16
Aluminium oxide (Al_2O_3)	..	..	..	..	14.40
Iron oxide (Fe_2O_3)	..	..	..	..	1.65
Magnesium carbonate (MgCO_3)	..	..	..	..	0.24
Calcium carbonate (CaCO_3)	..	..	..	..	2.55
Calcium sulphate (CaSO_4)	..	..	..	..	1.00

The chief physical properties are:

Specific gravity	..	..	..	2.39
Weight per cub. ft.	..	..	..	149 lbs.
Crushing resistance per sq. ft.	..	..	..	569 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	3.20

Both these stones can be employed for general building purposes, and also for heavy engineering work. They are uniform in colour and texture, and they exhibit strength and durability. For monumental work and all kinds of sculpture they are quite satisfactory. These stones are quarried in the Forest-of-Dean, Gloucestershire.

The undermentioned prices are for Forest-of-Dean stones,

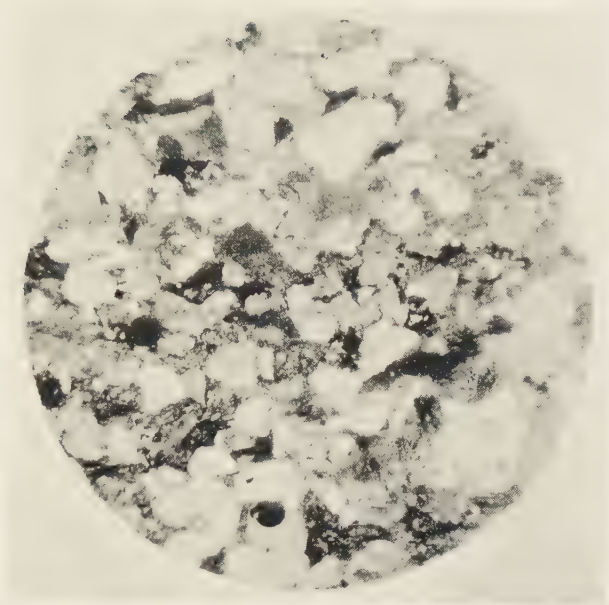


FIG. 14.—FOREST-OF-DEAN STONE (GREY)
Section magnified 30 diameters



FIG. 15.—FOREST-OF-DEAN STONE (GREY)
Section magnification 5



FIG. 15A.--FOREST-OF-DEAN STONE
(GREY)

To face p. 6q

PROPERTIES, DECAY, AND PRESERVATION 69

grey and blue, respectively, fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

GREY FOREST-OF-DEAN STONE.

Average type commercial building	..	19/-	per cube foot.
Fairly ornate church job		23/-	„ „ „

BLUE FOREST-OF-DEAN STONE.

Average type commercial building	..	21/-	per cube foot.
Fairly ornate church job		25/6	„ „ „

Gatton Stone (Merstham Stone, Reigate Stone, Firestone).—This stone occurs in the Upper Greensand deposits of the Upper Cretaceous series of the Cretaceous system. In colour it varies between a light whitish-grey and a pale greenish-grey. It contains a large quantity of fragmentary colloidal silica, a little mica (muscovite), and also a small quantity of glauconite. The slight greenish shade which is often possessed by this stone is due to the presence of glauconite. Silica and calcium carbonate are the natural binding materials, and it is the latter which contributes largely to the comparatively rapid rate of decay exhibited by this stone when exposed to polluted atmospheres.

Gatton stone is quite unsuitable for exterior work, and should be used only for interior work, in buildings in which the atmosphere can be considered clean and unpolluted. It has been used largely in the past for fireplaces, and in this application has given very satisfactory results. A good arris can be prepared on this stone, also a smooth face, and it is suitable for sculptured work. There are quarries still open in the neighbourhood of Godstone, Surrey, from which this stone may be obtained.

Chemical examination shows a large amount of calcium carbonate and a considerable quantity of silica, amounting to approximately 45 per cent. The specific gravity of this stone is 1.83, and its weight per cubic foot 102 pounds.

When this stone decays it not only laminates and scabs, but it also becomes very soft and falls to a fine powder when touched with the fingers.

Gifnock Liver Rock Stone.—This sandstone is quarried out of the Upper Limestone deposits of the Lower Carboniferous series (Carboniferous system). In colour it is light pinkish drab, and it is peppered with minute dark-coloured spots. It is moderately micaceous, and in structure it is compact and fine-grained. For building purposes it has been used largely in the neighbourhood of the quarry from which it is obtained. A comparatively smooth face and a fairly sharp arris can be worked on this stone.

On exposure to the weather it often develops a dark greenish-grey surface, and this in time forms a hard "skin" with a smooth surface. If this is carefully scraped off a foxy-red covering is found underneath. The material scraped off, on treatment with acid, effervesces vigorously, and analysis shows the presence of a considerable quantity of iron salts, with some compounds of the alkaline earths. This hard covering is no doubt formed by the action of rain-water in dissolving out of the stone some of the iron and alkaline earth compounds, and the solution thus formed, on coming to the surface, deposits the salts contained in it during the evaporation of the water.

The approximate chemical composition of this stone is as under:

Silica (SiO_2)	..	..	..	86.96
Aluminium oxide (Al_2O_3)	..	..	..	0.43
Iron oxide (ferric) (Fe_2O_3)	..	..	..	0.16
Iron oxide (ferrous) (FeO)	..	..	..	2.53
Calcium carbonate (CaCO_3)	..	..	..	6.00
Magnesium carbonate (MgCO_3)	..	..	..	2.98
Water and loss (H_2O)	..	..	..	0.94

The chief physical properties are:

Specific gravity	..	..	..	2.30
Weight per cub. ft.	..	..	..	143 lbs.
Crushing resistance per sq. ft.	..	..	..	459 tons
Absorption, per cent. of its dry weight	..	..	..	4.8

This stone is quarried at the Gifnock Quarries in Renfrewshire.

Hailes Stone.—This stone belongs to a group of calciferous sandstones occurring in the lower part of the Carboniferous Limestone series of the Carboniferous system. In colour it varies, there being light drab and light pink stones. There are three distinct varieties—viz., the Blue, Pink, and White; they all occur in the same quarry, and are suitable for all classes of building work. In chemical composition the Hailes stones are somewhat similar to the Craigleith stone, but there is a marked difference in the physical properties, all possessing a lower crushing strain and a higher absorption factor. The Hailes stones are quarried at Slateford, near Edinburgh.

White Hailes Stone.—This quality is light drab in colour, very compact and close-grained. It is the strongest of the three varieties, and contains the lowest percentage of ferrous and ferric iron. A smooth face and a fine arris can be prepared on it.

Its approximate chemical composition is as under:

Silica (SiO_2)	..	..	..	..	..	96.42
Aluminium oxide (Al_2O_3)	..	..	..	..	..	2.63
Iron oxide (ferric) (Fe_2O_3)	..	..	..	..	..	0.04
Iron oxide (ferrous) (FeO)	..	..	..	..	..	0.17
Calcium oxide (CaO)	..	..	..	..	..	0.39
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	0.25

The physical properties are as follows:

Specific gravity	..	..	..	2.33
Weight per cub. ft.	..	..	..	145 lbs.
Crushing resistance per sq. ft.	..	..	..	523.5 tons (Quarry)
Absorption, per cent. of its dry weight	..	..	..	4.2

Blue Hailes Stone.—In colour this variety is similar to the white, being light drab, but it is marked with fine lines of a bluish colour. It is a medium-grained stone, containing a small quantity of mica, and rather more ferrous and ferric iron than the white variety. Like the white stone this stone works up to a fine arris and smooth face.

It has the following chemical composition:

Silica (SiO_2)	..	..	..	..	..	93.28
Aluminium oxide (Al_2O_3)	..	..	..	..	..	3.23
Iron oxide (ferric) (Fe_2O_3)	..	..	..	..	..	0.02
Iron oxide (ferrous) (FeO)	..	..	..	..	..	1.82
Calcium oxide (CaO)	..	..	..	..	..	0.89
Magnesium oxide (MgO)	..	..	..	..	..	0.35
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	0.26

The chief physical properties are as under:

Specific gravity ..	..	..	..	2.39
Weight per cub. ft.	..	..	..	148 lbs.
Crushing resistance per sq. ft.	..	..	..	459.7 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	4.9

Pink Hailes Stone.—This variety is light pink in colour, compact, and fine-grained. It contains some mica and a larger amount of the oxides of iron than the other two varieties. In working it behaves very similarly to the white and blue qualities.

The approximate chemical composition of this stone is as under:

Silica (SiO_2)	..	..	..	..	..	96.82
Aluminium oxide (Al_2O_3)	..	..	..	..	..	0.87
Iron oxide (ferric) (Fe_2O_3)	..	..	..	..	..	1.49
Iron oxide (ferrous) (FeO)	..	..	..	..	..	0.29
Calcium oxide (CaO)	..	..	..	..	..	0.42

Its chief physical properties are as follows:

Specific gravity ..	..	..	..	2.3
Weight per cub. ft.	..	..	..	143 lbs.
Crushing resistance per sq. ft.	..	..	..	511.3 tons (Quarry)
Absorption, per cent. of its dry weight	..	..	..	5.5

The Hailes stones weather very well indeed in comparatively pure atmospheres, but should be used with caution in large manufacturing centres.

Ham Hill Stone.—This stone is a member of the Inferior Oolite series of the Jurassic system. The material of which

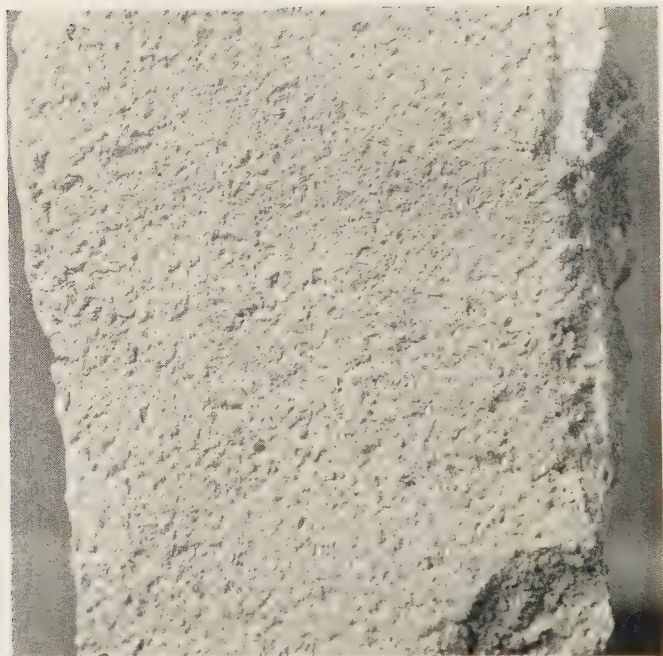


FIG. 16—HAM HILL STONE (YELLOW BED)

To face p. 73

it is composed was laid down in estuarine inlets subjected to a variation of tidal currents from time to time, with the result that the stone is not even in character. Current bedding is well developed, and it is very irregular, and along the beds layers of marl often occur, with occasional lenticular masses which are less consolidated than the general body of the stone. Ham Hill stone is an oolite, but the oolitic grains are relatively scarce, and they and shell fragments are set in a matrix of crystalline calcite stained very strongly by oxide of iron.

There are three qualities: the Yellow bed, the Grey bed, and the Brown bed, and they vary somewhat in characters. These stones are quarried at the Ham Hill Quarries, Norton, near Yeovil, Somerset.

The Yellow Bed (see Fig. 16).—The ground colour of this stone is light brown, and it is relieved by broad, irregular markings of a cream or buff tint, and also small dark brown spots. The irregular markings are due to shell fragments, and the spots to oxide of iron. A prepared or fractured surface sparkles on account of the presence of crystals of calcite. The matrix has an earthy appearance, but when examined by the microscope it is seen to be crystalline. Owing to the presence of comparatively large crystalline masses of calcite which constitute, together with the finer crystalline material, the matrix of the stone, this quality of Ham Hill stone is harder than the grey or brown beds. The comminuted shells are irregularly bedded, and not laid down in laminæ, as is the case with the grey bed, and there are very few ooliths to be seen. A sharp arris cannot be prepared on this stone; it is inclined to be ragged, and a faced surface is full of cavities owing to the removal of shell fragments and portions of the matrix during the working. It is not suitable for general building work in manufacturing centres; even plain ashlar is liable to serious decay. In the purer atmospheres of country districts this stone may be employed, but care must be used in its choice, and it is imperative to fix it on its natural bed.

The chemical composition of this stone is approximately:

Calcium carbonate (CaCO_3)	..	..	..	79·12
Magnesium carbonate (MgCO_3)	..	..	..	4·91
Silica (SiO_2)	..	..	..	4·56
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..	..	..	7·96
Water and loss (H_2O)	..	..	..	3·45

Its chief physical properties are as under:

Specific gravity	..	..	..	2·19
Weight per cub. ft.	..	..	..	135·6 lbs.
Crushing resistance per sq. ft.	..	..	..	207 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	7·67

The Grey Bed.—When dry this stone is medium brown in colour, with buff-coloured markings and purplish-brown specks. It is a moderately hard stone, but somewhat softer than the yellow bed, containing small spots composed of earthy-looking matter, which is chiefly calcium carbonate stained by oxide of iron. In character it is distinctly coarse-grained and crystalline, and the clastic is composed chiefly of disintegrated shells, the pieces being somewhat large in size; there are very few ooliths present. It is important to note that the comminuted shells are laid down in regular laminæ. The matrix of this stone is calcium carbonate, and it is crystalline in form. A worked face is rough in character, owing to the removal of shell fragments and some of the softer matrix during the process of preparation, and it takes on a more or less ragged arris.

On a washed face glistening crystals can be seen, and they are sparsely distributed. Like the grey bed this stone is useful for interior work, but should not be used for exterior buildings in towns and cities or at the seaside.

The approximate chemical composition of this stone is similar to the grey bed.

Average physical properties are as under:

Specific gravity	..	..	..	2·25
Weight per cub. ft.	..	..	..	140 lbs.
Crushing resistance per sq. ft.	..	..	..	259 tons (Royal Com.)
Absorption, per cent. of its dry weight	..	..	..	8·5

The Brown Bed.—The ground colour of this stone is light brown, but is somewhat darker than the yellow bed. It is very much speckled with cream to pale buff markings, and also with occasional dark brown and almost black spots. The latter are composed of very small particles of crystalline calcite stained by oxide of iron, whilst the former are due to comminuted shells. The shell fragments have been laid down very irregularly, and, with a very small quantity of ooliths, are cemented together by crystalline plates of calcite and finely divided calcite stained by oxide of iron. A glistening appearance is given to the stone by the plates of calcite. This variety of stone is not quite so hard as the yellow bed, but is harder than the grey bed; fragments broken off it can be reduced to a coarse granular powder if rubbed between the thumb and finger. It is a coarse-grained stone, which gives a much pitted face and a somewhat ragged arris. For general building purposes it cannot be recommended.

In the process of weathering it exhibits exfoliation, often after the formation of small or fair-sized scabs or blisters. It also decays comparatively rapidly along the lines of current bedding, forming deep furrows sometimes 1 inch wide and $\frac{1}{4}$ inch in depth. Before these furrows form the decaying stone becomes covered with excrescences of a scabby appearance which increase in size, whilst the substance beneath gradually disintegrates and becomes powdery. When the scabs fall off or are removed by wind and rain, the powdery stone underneath falls away, leaving a furrow which gradually increases in size as time goes on. Pitting is another type of decay which this stone undergoes, and often blocks in the plain ashlar of a building will develop large numbers of tiny pits on their surfaces.

Headington Stone (Shotover Limestone).—This stone occurs in the Upper Corallian group of the Middle Oolite series of the Jurassic system. The material of which this stone is composed, chiefly shell fragments, comminuted corals and coronæ of sea urchins, and portions of other marine organ-

isms, was laid down in comparatively clear seas which were subjected to varying currents, sometimes mud-bearing, and consequently the blocks of stone vary very much in quality. Current bedding is very irregular, and marly masses are not infrequent in occurrence. A great deal of the clastic (shell fragments, etc.) is poorly bound, owing to a scarcity of matrix, due to the manner in which this stone was formed. There are two chief varieties of this stone: one is of a dark cream colour, and the other light cream. The former is a little harder than the latter and less cellular, but neither of them has proved suitable for general building purposes. In the past this stone was largely employed in and around Oxford, and a great many of the colleges and ecclesiastical buildings in this city, erected during the eighteenth and the early part of the nineteenth century, were built with this stone. At the present moment they are in a deplorable state of decay, and efficient preservative treatment seems desirable.

Hollington Stones.—These sandstones are quarried from the beds of the Keuper series of the Triassic system. The material of which they are composed was laid down in the great inland Keuper sea or lake, most probably in those positions where rapid streams ran into it. Current bedding can be frequently observed in these stones, especially when wetted, usually in the form of thin lines of a slightly darker shade than the ground colour of the stone. The texture varies a little from fine to slightly coarse, and is usually very even, the slightly coarser varieties generally showing the least signs of current bedding. The sand grains of which these stones are chiefly composed consist mainly of quartz, there being small quantities of fragments of feldspars, tourmaline, and white mica (muscovite), and they are cemented together by silica with a little iron oxide (Fe_2O_3) as a subsidiary binder.

There are three chief varieties of Hollington stone—viz., Red, Mottled, and White—and in some cases the three kinds occur in the same quarry.



FIG. 17.—HOLLINGTON STONE (RED)

To face p. 77

The Red Hollington stone (see Fig. 17) is fine-grained to slightly coarse-grained, even in texture, often showing more or less faintly a current bedding, and it is of a bright red colour. It is not a difficult stone to work; it carries a fairly sharp arris, and a prepared surface is only moderately smooth. For general building work it may be employed with confidence, and it lends itself to sculpture.

The Mottled Hollington stone is even-textured, fine to slightly coarse-grained, and it is mottled or banded in several shades of red and drab. Like the red stone, it can be used for general building purposes or for carved work.

The White Hollington stone is obtained in two qualities, white firsts and white seconds. In colour the two qualities are very much alike, being a light pinkish-drab, but the texture differs, that of the firsts being medium-grained, and that of the seconds coarse-grained; both qualities are micaceous. These stones may be employed for general building work, but they are not so suitable for carved work as the red and the mottled, owing to their coarser structure. It should be noted that the second quality is very suitable for engineering work.

The Hollington stones may be classed among the best sandstones to employ for building purposes, especially in towns the atmospheres of which are polluted, owing to the excellent weathering properties exhibited by them.

An examination of a thin section of this stone (see Figs. 18 and 19) under the microscope shows that the larger quantity of the sand grains are angular or sub-angular in form, the balance being rounded (wind-borne sand). Distributed among the comparatively coarse sand grains are to be seen masses composed of very tiny angular grains, so tiny, in fact, that if a portion of disintegrated stone be stirred in water they remain in suspension for upwards of two minutes after the heavier and larger grains have settled to the bottom of the vessel. The sand appears to be more or less completely covered with oxide of iron in the case of the red and mottled varieties. The grains are closely packed,

and the cementitious material runs in thin lines between each grain of sand. Quartz is the chief constituent of the sand, fragments of felspar, tourmaline, hornblende, and mica occurring in small quantities.

A chemico-physical examination of this stone indicates that the sand grains are bound together chiefly by silica, iron oxide acting as a subsidiary binder.

The chemical composition of the Hollington stones varies a little, chiefly in regard to the content of oxide of iron. A typical analysis of the white stone is given below:

Silica (SiO_2)	..	..	..	86.64
Aluminium oxide (Al_2O_3)	..	..	..	8.78
Ferric oxide (Fe_2O_3)	..	..	..	1.02
Calcium oxide (CaO)	..	..	..	0.72
Magnesium oxide (MgO)	..	..	..	0.44
Alkalies	..	..	..	0.44
Sulphuric anhydride (SO_3)	..	..	..	trace
Carbonic anhydride (CO_2)	}	..	..	1.96
and combined water (H_2O)				

The chief physical properties (approximate) are as under:

RED HOLLINGTON STONE.

Specific gravity	..	..	..	2.17
Weight per cub. ft.	..	..	..	135 lbs.
Crushing resistance per sq. ft.	..	..	..	289 tons
Absorption, per cent. of its dry weight	..	..	..	5.8

MOTTLED HOLLINGTON STONE.

Specific gravity	..	..	..	2.21
Weight per cub. ft.	..	..	..	138 lbs.
Crushing resistance per sq. ft.	..	..	..	325 tons.
Absorption, per cent. of its dry weight	..	..	..	6.20

WHITE HOLLINGTON STONE.

Specific gravity	..	..	..	2.13
Weight per cub. ft.	..	..	..	133 lbs.
Crushing resistance per sq. ft.	..	..	..	260 tons.
Absorption, per cent. of its dry weight	..	..	..	5.4

These stones are quarried at the Hollington Quarries, Stoke-on-Trent, Staffordshire.

The undermentioned approximate prices are for Hollington

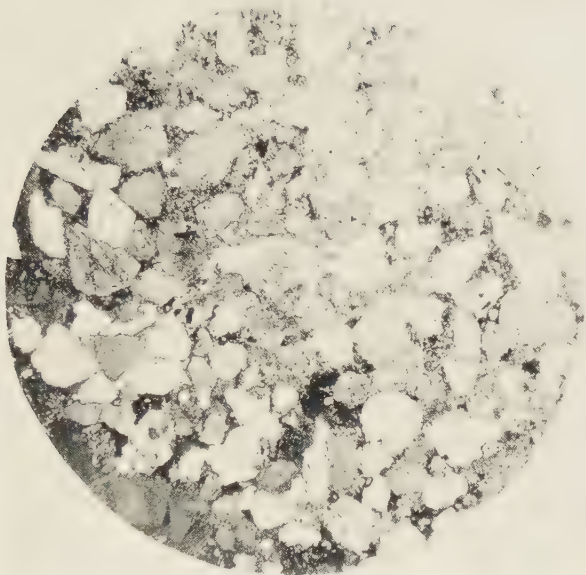


FIG. 18.—HOLLINGTON STONE (RED)
Section magnified 30 diameters

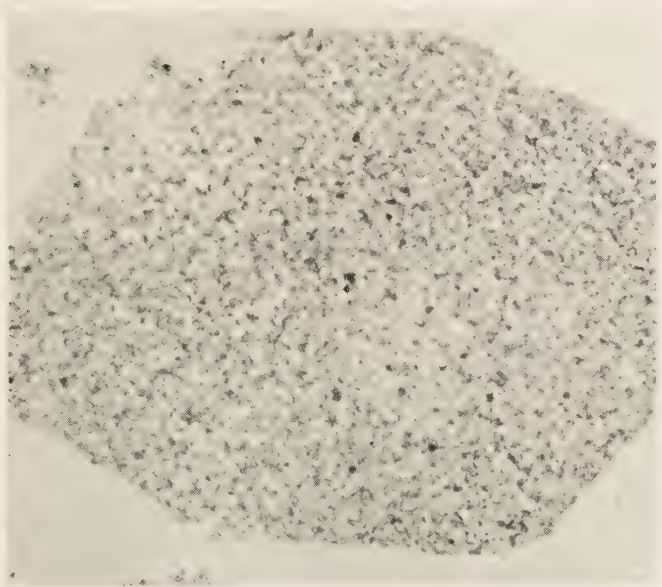


FIG. 19.—HOLLINGTON STONE (RED)
Section magnification 5

stones, red and mottled respectively, fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for London district only; transport and wages would modify them for different parts of the country.

HOLLINGTON STONE (RED).

Average type commercial building	..	18/6	per	cube	foot.
Fairly ornate church job	..	21/6	„	„	„

HOLLINGTON STONE (MOTTLED).

Average type commercial building	..	17/6	per	cube	foot.
Fairly ornate church job	..	20/6	„	„	„

Hopton Wood Stone.—This is a crinoidal limestone which occurs in the Carboniferous Limestone series of the Carboniferous system. The rock from which this stone is quarried was deposited, in all probability, on slopes in the seas of the Carboniferous period. It is built up chiefly of comminuted parts of brachiopods, mollusca, crinoids, polyzoa, corals, and foraminifera. In colour it varies between light grey and light drab, and in structure it is compact, fine-grained, and highly fossiliferous. A smooth surface will take a good polish, and on account of this property it is sometimes wrongly called a marble. Some of the Hopton Wood stone is very highly crystalline, and this appears to be due to the fact that the original fossil fragments, which in this stone are comparatively small, have undergone a recrystallization, and in this process almost lost their characteristic shapes; a fractured surface, ignoring the colour, has the appearance of coarse cube sugar. Other qualities of Hopton Wood stone contain a fairly large amount of very fine material, and the shape of the fossils is well defined. The original crystalline structure is much changed owing to secondary crystallization, and the stone is bespeckled with dark grey glistening masses, many of which are geometrical in form. The Hopton Wood stones are very hard, and a smooth face and sharp arris can be produced on them. The fine qualities can be employed for monu-

mental and sculptural work. In clean atmospheres it weathers very well, but it should not be used in buildings exposed to the polluted atmospheres of cities and towns. For interior decorations, especially when polished, it is very suitable.

If a thin section of this stone (see Figs. 20 and 21) is microscopically examined, it is seen to possess a highly crystalline structure, the portions of shells, crinoid stems, etc., being bound by "plates" of calcite. Some of the fossil fragments are stained by oxide of iron to a dark brown colour, and veins of this material run along the edges of the crystalline "plates" of calcite.

The approximate chemical composition of this stone is:

Calcium carbonate (CaCO_3)	..	..	..	98.40
Magnesium carbonate (MgCO_3)	..	..	..	0.32
Iron oxide (Fe_2O_3)	..	..	..	0.31
Silica (SiO_2)	..	..	..	0.77
Water and loss (H_2O)	..	..	..	0.20

It possesses the following chief physical properties:

Specific gravity	..	..	..	2.54
Weight per cub. ft.	..	..	..	158 lbs.
Crushing resistance per sq. ft.	..	..	..	806 tons (Rivington)
Absorption, per cent. of its dry weight	..	..	..	4.7

This stone is quarried at the Hopton Wood Quarries, Middleton, Derbyshire.

When this stone decays it does so in a very similar manner to Portland stone, weathering back evenly and allowing the harder fossil fragments to stand out from the surface.

Howley Park Stone.—This stone occurs in the Coal Measures series of the Carboniferous system. It is a light brown, fine-grained sandstone, free from laminations or current bedding, and homogeneous in structure. The sand grains are chiefly quartz, and the matrix is composed mainly of silica, there being a small quantity of iron oxide and calcium carbonate. A moderately smooth surface can be prepared on it, and it takes a fine arris. As sandstones go it cannot be considered hard, but it is durable and weathers very

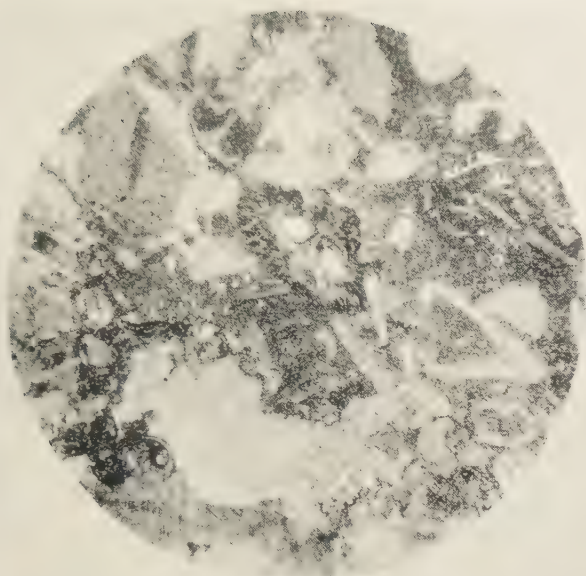


FIG. 20.—HOPTON WOOD STONE
Section magnified 30 diameters



FIG. 21.—HOPTON WOOD STONE
Section magnification 5

To face p. 8c

well, even in large cities. This stone lends itself to general building work, also sculptural and monumental work. Before using in a district surrounded by a polluted atmosphere, advice should be sought. Howley Park stone is quarried at the Howley Park Quarries, near Morley, Yorkshire.

Its chief physical properties are as under:

Specific gravity	2.26
Weight per cub. ft.	141 lbs.
Crushing resistance per sq. ft. ..	466.7 tons (Beare)
Absorption, per cent. of its dry weight	4.85

Huddlestone Stone.—This is a magnesian limestone occurring in the Middle Permian series of the Permian system. When dry it is light cream in colour, fine-grained, and distinctly crystalline. It consists mainly of small rhombs of dolomite closely packed together, and distributed throughout the mass are numbers of tiny irregular cavities, some of which contain well-developed crystals and others cryptocrystalline material. A freshly fractured surface is crystalline and somewhat sugary in appearance. The current bedding of this stone is irregular, and occasionally hard crystalline veins occur. It is a softish stone, and lends itself to the preparation of a smooth face and a sharp arris, and it can be sculptured. Like all the magnesian limestones it is quite unsuitable for building work in towns and cities, particularly those whose atmospheres are polluted. The Huddlestone Quarries have been worked for considerably over 400 years, but at present they are closed.

Its chemical composition is as under:

Calcium carbonate (CaCO_3)	53.82
Magnesium carbonate (MgCO_3)	41.46
Silica (SiO_2)	2.41
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3) ..	0.38
Water and loss (H_2O)	1.93

The chief physical properties of the stone are:

Specific gravity	2.21
Weight per cub. ft.	137.5 lbs.
Crushing resistance per sq. ft. ..	278 tons (Rivington)
Absorption, per cent. of its dry weight	8.2

Of the chief magnesian limestones used for building purposes this is the weakest. Roche Abbey stone is very similar to Huddlestone stone in its characters.

Huddlestone stone has been used in many of our historical buildings, and some of these are now in a sad state of decay. This stone decays very similarly to Anston stone (see p. 40). The fine powder which falls off decaying portions of this stone shows, when examined under the microscope, a large quantity of fragments of dolomite prisms mostly covered with very tiny crystals of a secondary nature.

Kenton Stone (Kenton Freestone).—This stone is quarried out of the Millstone Grit series of the Carboniferous system. There are two qualities of this sandstone, one being light drab in colour, slightly micaceous and medium-grained in texture, and the other of a light brown colour and texturally fine-grained. The sand grains of which this stone is composed are angular in shape, and composed chiefly of quartz, a little felspar being present. They are bound together mainly by a silica matrix, the subsidiary binding material being calcite. The presence of the latter substance constitutes a slight weakness from a weathering point of view. A sharp arris and a comparatively smooth surface can be prepared on this stone, and it is suitable for general building and sculptural work. This stone is quarried at the Kenton Quarries, near Newcastle.

Its approximate chemical composition calculated on the dry stone is:

Silica (SiO_2)	..	..	..	..	..	93.4
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..	..	..	..	..	2.1
Calcium carbonate (CaCO_3)	..	..	..	..	..	4.5

Those physical properties which have been determined show that the two qualities of this stone are very close.

	<i>Specific gravity.</i>		<i>Weight per cub. ft.</i>
Light drab	..	2.24	139 lbs.
Light brown	..	2.30	143 lbs.

Exfoliation is the chief form of decay exhibited by this stone.

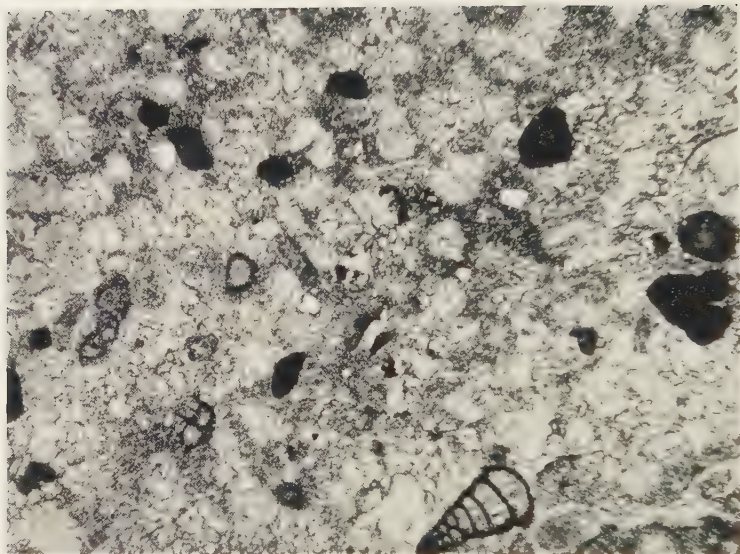


FIG. 22.—KENTISH RAG STONE
Section magnified 40 diameters

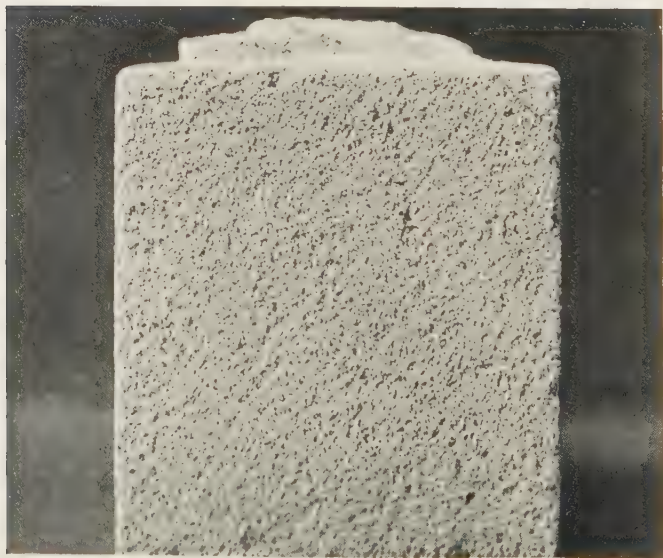


FIG. 23.—KETTON STONE

To face p. 83

Kentish Rag Stone.—This stone belongs to the Hythe beds of the Lower Greensand deposits of the Cretaceous system. In colour it is greenish-grey, and in structure compact and crystalline. The material of which it is composed was deposited in seas of some considerable depth; similar deposits are being formed at the present day off certain continental coasts in depths of from 50 to 500 fathoms. Much of the original material was undoubtedly pelagic, and as the living organisms died they dropped to the bottom of the seas. Kentish Rag contains abundant remains of foraminifera tests, and grains of quartz and of glauconite are more or less liberally dispersed through its mass; and occasionally small pebbles of palæozoic rocks (such as a red granite) are found. In all probability some of the quartz grains originate from the breaking down of the tests of arenaceous foraminifera (these tests during the life of the animals consist of particles of sand bound together by a ferruginous cement). The glauconite occurs to a considerable extent in the form of granules, which are deposited as casts in the chambers of foraminifera, and often left exposed by the solution of the calcareous shells themselves. The matrix or binding material of this stone is calcite, and it is distinctly crystalline. Kentish Rag is a stone of very variable character, and this fact must be considered if it is desired to use it for building purposes.

Kentish Rag is to be seen in many of our historical buildings, and quite a large number of churches and other structures in the south and south-east of England. Being somewhat difficult to work, the stone does not find general application in building work; it can be used for uncoursed random-rubble, regular coursed rubble, and similar kinds of work. It has been used for window tracery and other types of enrichments, and a sharp arris can be prepared on it.

It is quarried at the Allington Quarries, Allington, near Maidstone, Kent.

The chemical composition of this stone varies a

good deal, and the following figures may be taken as approximate:

Calcium carbonate (CaCO_3)	..	..	91.2
Silica (SiO_2)	..	..	4.8
Aluminium oxide (Al_2O_3)	..	..	2.9
Iron oxide (Fe_2O_3)	..	..	0.6
Water and loss (H_2O)	..	..	0.5

Its approximate physical properties are:

Specific gravity	..	..	..	2.69
Weight per cub. ft.	..	..	..	167 lbs.

A thin section of Kentish Rag, when examined under the microscope, shows a mass of crystalline calcite, mosaic in appearance, in which are embedded sections of various forms of foraminifera casts, particles of glauconite, and a small quantity of sand grains. The whole mass has a very compact appearance (see Fig. 22).

When this stone decays it usually exfoliates, the thickness of the laminæ varying on an average from $\frac{1}{16}$ to $\frac{1}{8}$ inch. Occasionally a form of crumbling appears, due to a loosening of the sand grains.

Ketton Stone (see Fig. 23).—This stone occurs in the upper part of the Lincolnshire Limestone deposits of the Inferior Oolite series (Jurassic period). It is yellowish-brown in colour, medium-grained, and completely oolitic in structure; in fact it is the finest example of an oolitic stone extant. The material of which Ketton stone is composed was in all probability formed in shallow seas subjected to frequent alteration in currents, and on this account the stone beds are subject to frequent and rapid variation, not only in regard to their thickness, but in the nature of their physical state. The oolitic grains are comparatively even in size and perfectly developed, and they are mixed with a very small quantity of shell fragments. A fresh fractured surface looks exactly like cod's roe, and a prepared surface is very rough and full of small cavities, due to the removal of numbers of ooliths during the process

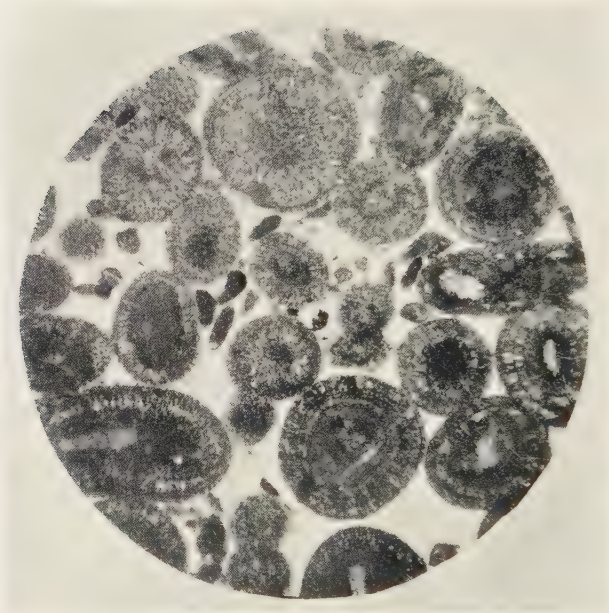


FIG. 24.—KETTON STONE
Section magnified 30 diameters. Note radial and concentric structure of oolites and absence of the usual calcite binding material

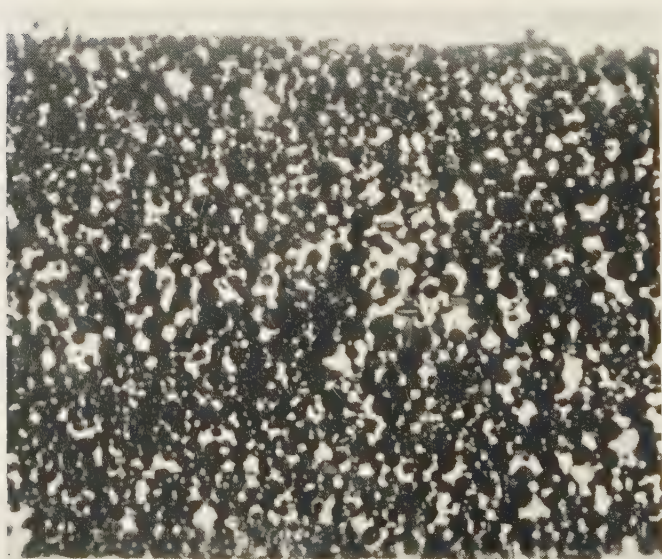


FIG. 25.—KETTON STONE
Section magnification 5. Note dumb-bell shape bodies which are two oolites connected together by a "peg" of calcite

of preparation. The ooliths and other portions of the clastic are not bound together in quite the same manner as in the general run of oolitic limestones; in fact this stone is destitute of what is usually understood by a cementing matrix, and Harker considers that the original matrix has been in great measure removed by solution. The individual ooliths and other portions of the clastic are united to their neighbours by somewhat peg-shaped pieces of crystalline calcium carbonate; this renders the stone very porous and somewhat weak in structure if compared with, say, Portland stone. It is not now possible to obtain original Ketton stone (which is light pinkish-brown in colour), as the quarries are exhausted. The stone from the new quarries at Stamford, and Edithwestern stone from the Edithwestern quarries, Stamford, are very similar in structure.

A thin section of this stone (see Figs. 24, 25, and 26), when examined microscopically, shows a very open structure, and the ooliths appear united together in two ways. A very large number of them are bound together by somewhat peg-shaped masses of crystalline calcite approximately one-half to three-quarters the size of the ooliths themselves, while others almost touch and are united by thin films of calcite. The greater number of the ooliths show a concentric structure formed round nuclei of various shapes, and some of the nuclei are quite crystalline. In many of the ooliths a radial structure is visible, and in others both the concentric and radial structures appear to be lost, and they look like balls of granular crystalline material. A number of the ooliths are coloured light brown with oxide of iron.

This stone has been employed for many years for dressings, mullions, enrichments, and general building work, although sharp arrises and a smooth face cannot be worked on it.

Ketton Rag is somewhat similar to Ketton stone in colour and oolitic structure, but it is heavier and much more consolidated. This is due to a difference in the form of the calcite matrix or binding material, which not only fills all the spaces between the ooliths, but large crystals of it

enclose a considerable number of ooliths. These crystals are packed close together, and it is to them that the characteristic lustre mottling on a prepared surface of this stone is due. This stone is frequently traversed by veins of calcite, which also distinguish it from Ketton stone. Whilst the Rag is very hard and strong, it is unsuitable for general building purposes owing to its somewhat easy disintegration by frost.

The approximate chemical composition of Ketton stone is as follows:

Calcium carbonate (CaCO_3)	..	..	..	..	91.89
Magnesium carbonate (MgCO_3)	..	..	..	..	4.32
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..	..	..	..	1.02
Water and loss (H_2O)	..	..	..	..	2.77

Note.—In some specimens approximately 0.2 per cent. of silica (SiO_2) is present.

Its chief physical properties (average) are:

Specific gravity	..	..	..	2.25
Weight per cub. ft.	..	..	..	140 lbs.
Crushing resistance per sq. ft.	..	..	..	101.7 tons (Beare)
Absorption, per cent. of its dry weight	..	..	..	9.2

When Ketton stone decays two chief forms present themselves. One of these is exfoliation, and in this type of decay narrow cracks first appear in the stone, in many instances several in parallel, and these cracks gradually become wider and wider until pieces separate and fall off. The cause of the cracks and their expansions is the formation and crystallization of calcium sulphate. Close examination of exfoliated portions will often reveal a quantity of tiny crystals of this substance among and over the surface of the ooliths. The cracks often form at right angles and parallel to arrises, and when they open out the stone appears to expand and the arrises turn up.

The other chief form of decay is the corroding away of the ooliths. These either weather away evenly to a flat



FIG. 26.—KETTON STONE

Portion of section highly magnified showing peg-shape masses uniting the ooliths.
Note the light patches are open spaces

To face p. 86

surface or the outer surface dissolves away first and then the interior, leaving in very many cases a cup-like depression (probably due to the falling out or rapid decay of the nuclei). This form of decay often takes place to some distance below the surface of the stone.

Often the surface of this stone becomes more or less temporarily hardened, and if this surface is broken loose ooliths will pour out in quantity. This is no doubt due to the removal by solution of the peg-like calcite linkages between the ooliths.

Ketton Rag decays by exfoliation, due to frost and the formation of crystals of calcium sulphate, and also by a more or less even weathering back which throws up the fossils and calcite veins in relief. The ooliths themselves decay similarly to those in Ketton stone.

Leckhampton Stone (see Fig. 27).—This stone occurs in the Inferior Oolite of the Jurassic system. It is light cream in colour, and is peppered with tiny, very light brown spots. In structure it is medium-grained and distinctly oolitic, the ooliths being comparatively large and bound together by a matrix of calcite. Current bedding is obvious, and it is marked by layers of comminuted shells. This stone contains a small quantity of plates of calcite which give a prepared surface a glistening appearance. In the mass occur some fairly large cavities filled with a grey chalky-looking material which is very hard, and to the naked eye appears non-crystalline; microscopical examination shows it to be composed of very tiny crystals of calcite. A faced surface is somewhat rough, owing to a large number of tiny cavities which are produced during its preparation; it is possible to obtain moderately sharp arrises.

Leckhampton stone is quarried at the Quarries, Leckhampton, Gloucestershire, and it has been largely used for general building purposes in the Gloucester and Cheltenham districts. In clean atmospheres this stone will weather quite well, but it is liable to attack in the polluted atmospheres of cities and towns in manufacturing centres.

Its approximate chemical composition is as under :

Calcium carbonate (CaCO_3)	..	..	..	..	96.20
Magnesium carbonate (MgCO_3)	..	..	..	..	0.70
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	0.82
Silica (SiO_2)	..	..	..	..	0.56
Water and loss (H_2O)	..	..	..	..	1.72

The averages of some of its physical properties are :

Specific gravity	..	..	..	..	2.23
Weight per cub. ft.	..	..	..	..	139 lbs.
Crushing resistance per sq. ft.	..	..	..	..	201 tons.
Absorption, per cent. of its dry weight	..	..	..	..	5.36

Mansfield Woodhouse Stone.—This is a magnesian limestone or dolomite occurring in the Permian beds of the Permian system. It has a rich yellow colour, and in texture it is very fine-grained and very compact. On account of the latter property it is possible to produce a fairly good polish on a prepared surface. In all probability this stone was formed in a similar manner to Anston stone. It is composed chiefly of small well-formed rhombs of dolomite, and scattered about its mass are minute specks of black oxide of manganese. The beds of this stone are irregular, and in some parts the mass is more crystalline than in others. A fresh fractured surface has a distinct crystalline appearance.

A sharp arris can be prepared on this stone, and it lends itself to the production of fine sculptured work. It has been used for dressings and general building work, but its poor weathering properties, especially in polluted atmospheres, has restricted its use to internal decoration work. Mansfield Woodhouse stone is quarried at the Mansfield Quarries, Nottingham.

The approximate chemical composition of this stone is:

Calcium carbonate (CaCO_3)	..	..	..	..	52.23
Magnesium carbonate (MgCO_3)	..	..	..	..	42.55
Manganese dioxide (MnO_2)	..	..	..	..	0.21
Silica (SiO_2)	..	..	..	..	3.20
Water and loss (H_2O)	..	..	..	..	1.81



FIG. 27. LECKHAMPTON STONE (SHELL BED)



FIG. 28. MANSFIELD STONE (RED)

To face p. 88

Its chief physical properties are given under :

Specific gravity	2·34
Weight per cub. ft.	145·5 lbs.
Crushing resistance per sq. ft. ..	577 tons (Rivington)
Absorption, per cent. of its dry weight	4·75

This stone decays in a very similar manner to Anston stone (see p. 40).

Mansfield Stones.—The Mansfield stones are quarried from the Permian deposits of the Permian system. They are dolomitic sandstones, or in other words, sandstones containing a large quantity of dolomite. In colour the Mansfield stones vary from a warm yellow to a warm red; the former is known in the trade as White Mansfield, and the latter, together with several lighter shades of red, as Red Mansfield (Fig. 28). It should be noted that the colour of individual blocks may vary between light pink and dark red. In texture they are fine-grained and compact, and current bedding is usually very evident and frequently very irregular; the lines of current bedding are often very thin and close together. The sand grains of these stones consist to a very large extent of quartz, and there are also small quantities of felspar and hornblende. It is highly probable that these sand grains are the result of disintegration of the Carboniferous rocks. Dolomite in the crystalline form and stained by oxide of iron is the chief binding material, calcium carbonate and silica acting as subsidiaries. The Mansfield stones lend themselves to the preparation of smooth surfaces, sharp arrises, and they can be sculptured. They should not be used in cities and towns whose atmospheres are polluted; especially in London, Birmingham, Sheffield, Manchester, Rochdale, Leeds, and similar manufacturing centres.

If a thin section of Mansfield stone is examined under the microscope it will be seen that the sand grains are sub-angular and angular (some of them have very sharp angles), and they are comparatively far apart. The matrix is distinctly crystalline, and is darkened by iron oxide, and

contains a considerable quantity of tiny dark specks (see Figs. 29 and 30).

After boiling a fragment of Mansfield stone in hydrochloric acid until all soluble material has been extracted, microscopical examination shows numbers of cavities and some of the sand grains partly bound together by silica, whilst others lie loosely against their neighbours.

These stones are quarried at the Sills and Lindley Quarries, Mansfield, Nottinghamshire.

The approximate chemical compositions of these stones are:

WHITE.						
Silica (SiO_2)	..	..	..	..	..	51.62
Calcium carbonate (CaCO_3)	..	..	..	..	..	26.58
Magnesium carbonate (MgCO_3)	..	..	..	..	..	18.16
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	..	1.58
Water and loss (H_2O)	..	..	..	..	..	2.06

RED.						
Silica (SiO_2)	..	..	..	..	..	50.52
Calcium carbonate (CaCO_3)	..	..	..	..	..	26.80
Magnesium carbonate (MgCO_3)	..	..	..	..	..	17.91
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	..	..	3.72
Water and loss (H_2O)	..	..	..	..	..	1.05

In regard to physical properties the averages of these will be found under:

WHITE.						
Specific gravity	..	..	..	..	..	2.26
Weight per cub. ft.	..	..	..	..	..	141 lbs.
Crushing resistance per sq. ft.	..	..	..	..	..	463 tons.
Absorption, per cent. of its dry weight	..	..	..	..	..	5.23.

RED.						
Specific gravity	..	..	..	..	..	2.24
Weight per cub. ft.	..	..	..	..	..	139 lbs.
Crushing resistance per sq. ft.	..	..	..	..	..	601 tons.
Absorption, per cent. of its dry weight	..	..	..	..	..	4.67

Speaking broadly, these stones decay very badly in most towns and cities. The most characteristic form of decay is exfoliation, and often the exfoliated portions are of a

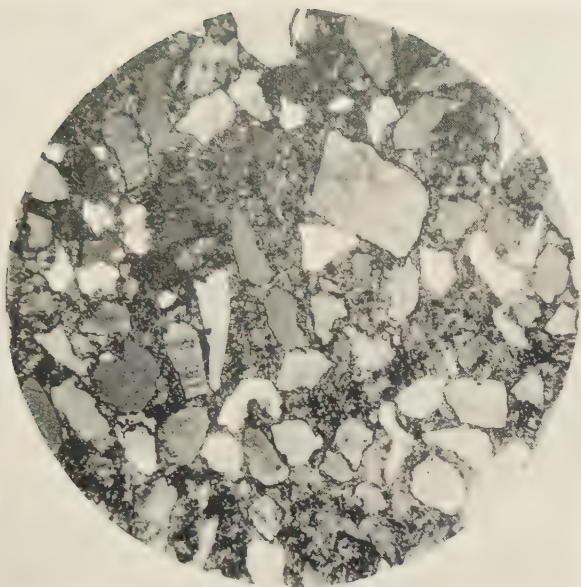


FIG. 29.—MANSFIELD STONE (RED)
Section magnified 30 diameters

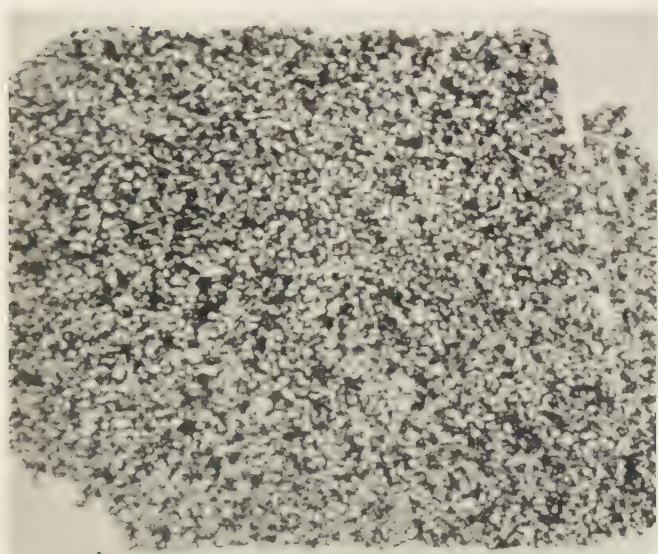


FIG. 30. MANSFIELD STONE (RED)
Section magnification 5

thickness of 3 inches or more, and 2 or 3 feet in length. Generally the splitting takes place along the lines of current bedding, and between the laminæ are to be found crops of crystals of calcium sulphate. Another type of decay exhibited by these stones is the formation of deep furrows or channels along the lines of current bedding, and this is most frequently seen on plain ashlar. At times a peculiar kind of weathering occurs, chiefly on the surface of coarse enrichments such as the scrolls of trusses, etc. A large scab forms on the stone, the surface of which is quite hard and shows no signs of decay. This eventually cracks, and growing crystals of calcium sulphate beneath push it away from the main body of the stone. When this is removed by hand, or comes away naturally in the course of time, the stone underneath is found to be very soft to a depth of between $\frac{1}{8}$ and $\frac{1}{4}$ inch.

Minchinhampton Stone (the Weather Stone Quality: see Fig. 31).—This stone is quarried from the Great Oolite deposits of the Jurassic system. Whilst it is an oolitic stone it contains very few ooliths, being composed, as far as the clastic is concerned, almost entirely of comminuted and whole shells; the clastic is bound together by crystalline calcite. There are many cavities in this stone, some of which measure $\frac{1}{8}$ inch and even more in diameter, and a number of which are filled with sandy material. In colour Minchinhampton stone varies between a rich cream and buff, and in texture it is coarse, porous, and very liable to variation. It is hard, and not easy to work, and only a somewhat ragged arris and a rough face can be prepared on it. In the neighbourhood of the quarries, at Amberley, near Minchinhampton, it has been used for a considerable number of years. Its porous nature renders it unsuitable for general building purposes in cities and towns, or in fact in any exposed position, as it carries water easily, and is, therefore, liable to make damp the building in which it is used, and in polluted atmospheres it is susceptible to deep-seated decay.

Painswick Stone and Nailsworth Stone (Fig. 32).—These are limestones belonging to the Inferior Oolite series of the Jurassic system. As the material of which these stones is composed was deposited in shallow seas subjected to change in currents, it varies to some extent, and thus the quality of the stone is affected accordingly. Both are distinctly oolitic, and the ooliths, which are fairly uniform in size and somewhat smaller than those of Ketton stone, are packed closely together and bound by a matrix of crystalline calcite. Shell fragments are not very numerous, and small cavities are occasionally found.

These stones are very similar in appearance and texture, being light cream in colour, with a texture which is fine-grained and more or less granular. They are not very hard, and they can be worked to a smooth face and a fairly sharp arris. Unfortunately they are quite unsuitable for exterior work, but may be employed satisfactorily for all types of interior building. Both these stones have been used fairly largely in the vicinity of the quarries, at Painswick and Nailsworth, and owing to the fact that there are large quantities available there should be possibilities of a greater use for them in the future if submitted to a satisfactory preservative treatment.

Park Spring Stone.—This is a sandstone which is quarried out of the Coal Measures deposits of the Carboniferous system. It is light brown or yellowish-drab in colour, medium-grained in texture, and slightly micaceous. In cases in which colour will admit it may be used for general building work. Its chief physical properties are:

Specific gravity	2.44
Weight per cub. ft.	151.5 lbs.
Crushing resistance per sq. ft. ..	487 tons (Rivington)
Absorption, per cent. of its dry weight	6.2

Park Nook Stone.—This is a magnesian limestone which is quarried from the Middle Permian of the Permian system. Geologically it was formed in a similar manner to Anston stone, and it is composed almost entirely of fragments of



FIG. 31. MINCHINHAMPTON STONE

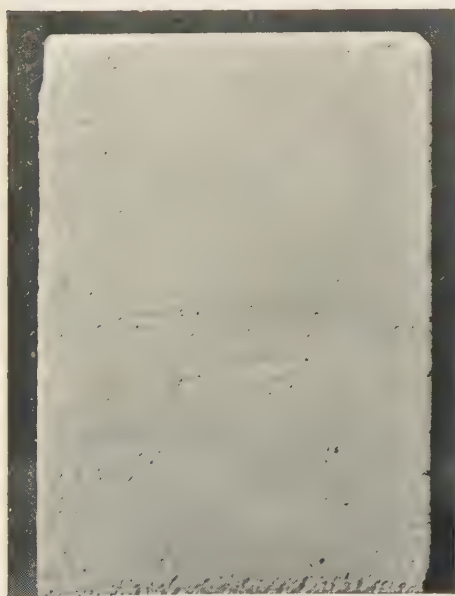


FIG. 32.—NAILSWORTH STONE
To face p. 92

polyzoa which during the course of time have been converted into dolomite, and which are cemented together by dolomite, which constitutes the matrix. Its colour varies from a light cream to a pale yellow, and in texture it is compact and fine-grained. A smooth face and a fine arris can be worked upon it, and it can be satisfactorily sculptured. As a stone for general building work it is not altogether suitable owing to its liability to decay somewhat rapidly, especially in polluted atmospheres.

Its approximate chemical composition is as under:

Calcium carbonate (CaCO_3)	..	..	..	..	56.1
Magnesium carbonate (MgCO_3)	..	..	..	..	42.2
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..	..	..	..	0.5
Water and loss (H_2O)	..	..	..	..	1.2

The chief physical properties are:

Specific gravity	..	..	..	..	2.14
Weight per cub. ft.	..	..	..	..	133 lbs.
Absorption, per cent. of its dry weight	..	..	..	..	6.8

Pennant Stone (Bristol).—This stone is quarried out of the Coal Measures deposits which occur in the Carboniferous system. It is a sandstone, the colour of which may be described as greenish or blue-grey, and in texture it is very fine-grained and compact. The sand grains which compose the clastic of this stone are chiefly of quartz, with a fair amount of felspathic material, and the matrix or binding material is mainly silica, with small quantities of the alkaline earth salts. Pennant stone is hard and strong; nevertheless it can be worked to a sharp arris and a smooth surface. It is very suitable for general building work, constructional engineering, and also for monumental purposes.

The chemical composition of this stone is somewhat variable; approximately it is as under:

Silica (SiO_2)	..	..	..	..	..	82.42
Aluminium oxide (Al_2O_3)	..	..	..	..	..	7.92
Iron oxides (Fe_2O_3 and FeO)	..	..	..	..	..	4.87
Calcium oxide (CaO)	..	..	..	..	..	0.49
Magnesium oxide (MgO)	..	..	..	..	..	0.71
Sodium and potassium oxides (Na_2O and K_2O)	..	..	..	..	..	0.81
Water and loss (H_2O)	..	..	..	..	..	2.78

Its chief physical properties are:

Specific gravity	2·76
Weight per cub. ft.	172 lbs.
Crushing resistance per sq. ft. ..	1,001 tons (Kirkaldy)
Absorption, per cent. of its dry weight	3·2

It is quarried at the Fish Pond Quarries, near Bristol.

Portland Stone.—This stone occurs in the Portland beds of the Upper Oolite series of the Jurassic system, and these beds are best developed at Portland and Swanage, whilst they are prolonged into France, near Boulogne. In the Portland formation there are three distinct beds of oolitic stones which find useful application in the building industry—viz., the roach, the whitbed, and the base or best bed. Portland stone was formed in moderately tropical shallow seas, and on this account is liable to change rapidly in quality in various parts of the strata; the stone from different parts of the Isle of Portland shows somewhat diverse characters, and this is even so from individual quarries. This variation in character is marked in the case of the three beds just mentioned, as will be seen from the following descriptions.

Roach.—This forms the top bed of the Portland limestone deposits, and it is 2 to 3 feet thick. When dry it is a light buff-coloured stone, somewhat oolitic in character, and usually coarse, tough, and full of cavities, which have been produced by the destruction of fossils by percolating waters, after the consolidation of the rock. These cavities are actually the casts and moulds of various fossils, the chief being *Cerithium Portlandicum* and *Trigonia gibbosa*, called by the quarry men “Portland screws” and “horse-heads” respectively. This coarse texture makes the stone unsuitable for general building work, as it will not take a sharp arris and a good face cannot be produced on it, but for constructional engineering, such as harbour work, it is a suitable material, and in this direction is largely employed.

Whitbed (Fig. 33).—This deposit occurs immediately beneath the roach, to which it is firmly attached, and the

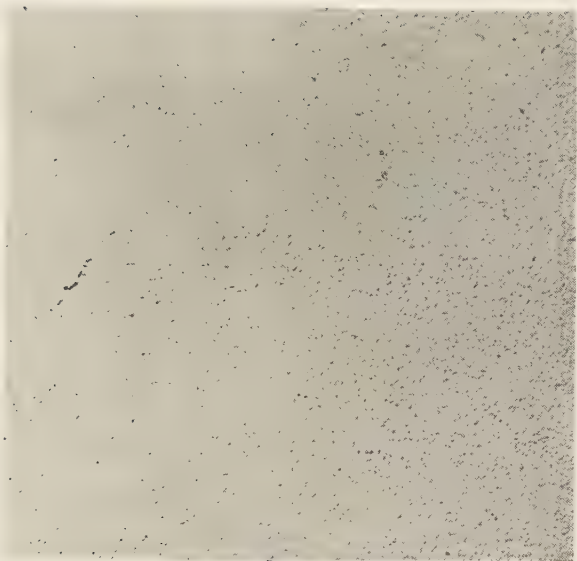


FIG. 33.—PORTLAND STONE (WHIT BED)

To face p. 94

thickness of the bed varies between 8 and 10 feet. When dry, the whitbed stone is of a light dove colour. It is comparatively close-grained, somewhat granular in appearance, and its oolitic nature is very marked. This stone contains a fair amount of obviously crystalline calcite in particles varying in size from tiny specks to pieces about $\frac{1}{16}$ inch. It contains a moderate amount of shell detritus which is irregularly distributed. To the naked eye the matrix has a chalky non-crystalline appearance, but under the microscope this is found to be crystalline. The texture of this stone varies somewhat. There are some patches containing large quantities of broken shells, and others of softer material, which occasionally show up very distinctly after the stone has been exposed to the weather. Current bedding is frequently exhibited in this stone, and in some cases it is irregular, but apparently this seems to produce no detrimental effect in regard to its weathering properties. A good arris and face can be produced on this stone, and the best grades are suitable for carved work.

Base Bed.—As the name implies, this strata occurs at the bottom of the Portland stone deposits, and it is not immediately below the whitbed, there being a deposit of flinty curf and base bed roach stone between. The thickness of the base bed varies between 5 and 6 feet. Dry base bed stone is of a cream colour, being somewhat paler than whitbed, and it is also finer in grain and not quite so granular. It contains a fair amount of shell detritus, a quantity of which is small in size, and interspersed throughout the mass of the stone, but not in any considerable quantity, are thin plates of calcite, which in a fresh fracture gives the stone a sparkling appearance. Like the whitbed, the matrix has a chalky and non-crystalline appearance, which under the microscope is seen to be distinctly crystalline. This stone is not quite so hard as the whitbed, and it does not weather so well in exposed positions. It is suitable for carved work, but as the stone is not quite so durable as whitbed, if it is used externally, care should be taken in regard to the

situation in which it is built. It takes a good arris and a good face can be formed on it.

Speaking generally, the true or natural bed of the Portland stone is somewhat difficult to distinguish, and there are occasions when the expert is deceived in regard to this matter. It is wiser and safer when fixing to lay this stone on its natural bed whenever it can be determined with certainty.

An examination of a thin section of Portland stone under the microscope shows clearly that the shell fragments and the oolitic grains are bound together by a matrix of calcium carbonate crystallized in the form of calcite (see Figs. 34 and 35). There are to be seen some crystals of calcite in the perfect rhombohedral form, and many of them are comparatively large and attached to the ooliths. The matrix has a peculiar mosaic appearance, and there are patches bespeckled with a large quantity of various-sized spots of a brown colour. The material which produces these spots is in all probability oxide of iron. The ooliths, speaking generally, are very closely packed, and they vary somewhat in size. Most of the ooliths are possessed of a nucleus which in some cases has a transparent but somewhat mosaic appearance, in other cases stained brown with somewhat darker spots of the same colour, and in others the nucleus is composed of a number of small sub-angular particles cemented together by calcite, or it consists of one particle which may be sub-angular, ovoid, or globular in shape. Many of the ooliths appear like mosaic, and are practically transparent throughout their whole mass; others are made up of a number of concentric layers of calcite covering the nucleus, and in many cases these layers are stained a light brown. The concentric layers are crystalline in structure, and some of them show a radial appearance which is due to a secondary crystallization. It is probable that these various crystallized states and formations determine to a certain extent the variation in weathering properties of different portions of Portland stone.

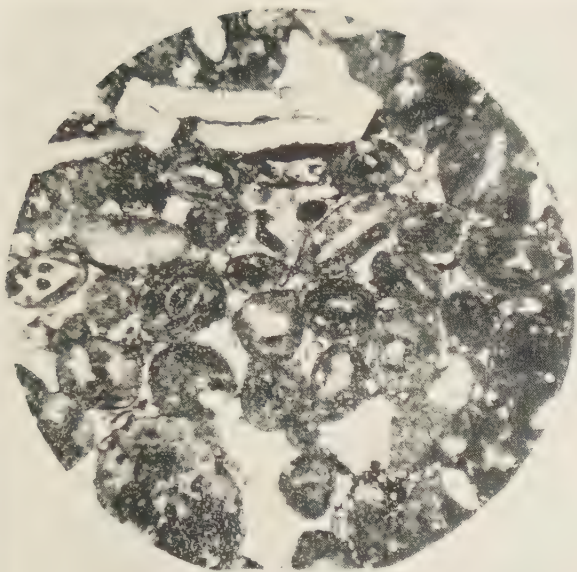


FIG. 34.—PORTLAND STONE (WHIT BED)
Section magnified 30 diameters. Notice the oolites and shell fragments. The very light patches are the calcite binding material

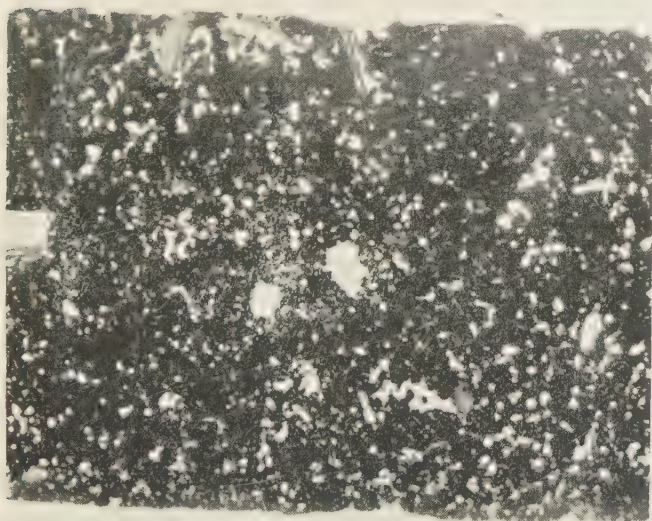


FIG. 35.—PORTLAND STONE (WHIT BED)
Section magnification 5. The large white patches are shell fragments
To face p. 96

Essentially Portland stone is an impure calcium carbonate, as will be seen from the approximate analysis given below, and owing to the small percentage of oxide of iron (Fe_2O_3) present it is comparatively pale in colour. It contains a small amount of silica, which exists chiefly in the form of quartz in the finely divided but crystalline state.

Calcium carbonate (CaCO_3)	..	..	..	95.80
Magnesium carbonate (MgCO_3)	..	..	..	1.20
Aluminium and iron oxides (Al_2O_3 and Fe_2O_3)	..	..	..	0.30
Silica (SiO_2)	..	..	..	1.30
Water and loss (H_2O)	..	..	..	1.40

The following figures relating to the physical properties of Portland stone will no doubt be of use to some readers, but it should be clearly understood that they are all approximate, for the reasons given at the commencement of this chapter.

	<i>Sp. Gr.</i> (average).	<i>Weight in</i> <i>lbs. per cub.</i> <i>ft. (average).</i>	<i>Crushing re-</i> <i>sistance, tons</i> <i>per sq. ft.</i> <i>(average).</i>	<i>Absorption,</i> <i>per cent. of its</i> <i>dry weight</i> <i>(average).</i>
Roach ..	2.28	142.5	—	—
Whitbed ..	2.12	132.2	204.7 (Beare)	7.5
Basebed ..	2.2	137.3	287.0 (Beare)	6.8

The manner in which the face of Portland stone decays when exposed to the weather varies somewhat. In a large number of cases the matrix seems to weather away quicker than the ooliths and the fossils which constitute the clastic, and in some specimens of stone which have decayed in this way it is possible to shake out the ooliths, as they are so loose owing to the complete dissolving away of the crystalline matrix. Another form of decay of Portland stone is due to the growth of crystals of soluble salts on the surface and in proximity thereto, which during this process breaks up the calcite matrix into very small particles almost dust-like in nature. This disintegration takes place until the ooliths are loosened and fall away. In many instances

a form of decay known as mottling or pitting is exhibited, the periphery of the pits being circular or oval in form with a basin-shape interior, and some of these pits may measure $\frac{1}{4}$ inch deep in the middle. There is no doubt that these pits indicate soft spots in the stone. A very frequent type of decay exhibited by Portland stone is that of scaling or scabbing, and this is usually the result of what might be considered as secondary decay; the initial decay causing the formation of a hard surface layer which consists of calcium sulphate, with a small quantity of calcium carbonate, and often some tarry and greasy material derived from soot. This hard surface is broken up in places by the crystallization of salts brought forward in the moisture and quarry sap contained in the stone, the crystals forming under the hard surface and eventually bursting it in places.

Another rather curious method of decay which often makes its appearance on enrichments and other carved work is that of "crazing" (formation of hair cracks), and finally bursting. Firstly, the member which is decaying exhibits a number of cracks running in several directions, and these after a time open up, and eventually pieces fall away. After this, disintegration takes place, chiefly by the destruction of the matrix. The form of decay most exhibited in Portland stone is that of weathering back of the matrix and the ooliths, leaving the harder calcite fossils standing out in bold relief, these fossils often corroding to a knife edge. Portland stone seems to vary considerably in regard to its susceptibility to attack by deleterious substances in the atmosphere, and this is particularly obvious in London. There are buildings in this city the Portland stone of which has decayed almost as badly in twenty to twenty-five years as some of the stone in St. Paul's Cathedral, and the Banqueting Hall at Whitehall, which is over 300 years old, seems to show less decay than the other national monument just mentioned. There are instances in which the weathering back of Portland stone in twenty-six years has amounted to $\frac{1}{8}$ inch.

The undermentioned approximate prices are for Portland stone (Whitbed) fixed complete, including the cost of scaffolding, based on large works, and calculated at the time of writing (March, 1926). These prices are for the London district only; transport and wages would modify them for different parts of the country.

Average type commercial building ..	19/6	per cube foot.
Fairly ornate church job	23/6	„ „ „

Prudham Stone.—This is a sandstone which is quarried from the Carboniferous Limestone deposits of the Carboniferous system. When dry its colour is warm brown, and it is slightly micaceous. In texture it can be considered as medium-grained, and in structure more or less compact. The sand grains of this stone consist largely of quartz with a small amount of felspathic fragments, and they are partly bound by silica; the subsidiary binding materials are small quantities of iron oxide and calcium and magnesium salts.

A moderately smooth surface and a fairly sharp arris can be prepared on this stone, and it can be employed for the various types of ashlar, moulded work, and enrichments. It has been used in several large buildings in various parts of Great Britain with moderately good results. In polluted atmospheres it is liable to weather badly.

This stone is quarried at Prudham in Northumberland.

Its average chemical composition is as under:

Silica (SiO_2)	86.45
Aluminium oxide (Al_2O_3)	6.39
Iron oxide (Fe_2O_3)	0.81
Magnesium oxide (MgO)	0.24
Calcium oxide (CaO)	0.62
Potassium oxide (K_2O)	0.19
Water and loss (H_2O)	5.30

The chief physical properties are:

Specific gravity	2.28
Weight per cub. ft.	142 lbs.
Crushing resistance per sq. ft. ..	455 tons.
Absorption, per cent. of its dry weight ..	4.10

Purbeck Stone.—This is a limestone quarried from the Purbeck beds, which occur in the Upper Oolite deposits of the Jurassic system. The Purbeck beds are divided into Upper, Middle, and Lower, and whilst the Middle beds are variable, containing marine, brackish, and freshwater deposits, the Upper and Lower beds are composed almost entirely of freshwater material. This indicates that the most suitable stone for building and similar purposes is to be obtained from the Upper and Lower beds.

The hardest Purbeck stone is known as Seacombe stone, sometimes as Purbeck Cliff stone. Unfortunately, the best exposures of the beds from which this stone is quarried are on the coast, and this introduces difficulties in the matter of transferring to ships for transport; railway facilities are not available. This and the hardness of the stone seems to have stood in the way of quarrying large quantities during recent years. Undoubtedly a demand for this stone will be created in the near future owing to its great suitability for general building purposes.

Another quality of Purbeck stone, called Pond stone, is also suitable for general building purposes. It is a hard, durable stone, which, like the Seacombe variety, allows of the preparation of a smooth surface and a sharp arris.

Purbeck stone, when dry, is pale yellow or rich cream in colour. Its approximate chemical composition is very similar to Portland stone (see p. 97), but its specific gravity is somewhat higher: Average specific gravity, 2.41; average weight in pounds per cubic foot, 150.

Quarella Stone.—This is a sandstone of a somewhat calcareous nature. It occurs in the Rhætic series of the Triassic system, and was in all probability formed in a salt lagoon on the border of a sea. In structure it is moderately fine-grained, and its texture is even, current bedding being more or less obscure. Its colour varies from white to grey, and it often possesses a greenish tint. The sand grains are chiefly bound together by a silica matrix, the subsidiary binding materials being magnesium and calcium salts.

Three distinct qualities are quarried, and their colours are white, grey, and light green. The white and light green qualities are used for general building work, and the grey for steps, landings, etc.

This stone weathers fairly well in clean atmospheres, but in polluted atmospheres it is attacked to a fair depth below the surface, becoming friable in the process. On this account careful consideration should be given to conditions before deciding to use it.

The green Quarella stone is light green in colour and fine-grained, whilst the white quality possesses a very slight green tint, and is of fine texture. Both qualities work to a moderately smooth face and fine arris, and they can be carved.

The average chemical composition of the Quarella stones is as under:

Silica (SiO_2)	..	..	..	91.02
Aluminium oxide (Al_2O_3)	..	..	..	3.42
Iron oxide (Fe_2O_3)	..	..	..	0.49
Calcium oxide (CaO)	..	..	..	1.18
Magnesium oxide (MgO)	..	..	..	0.28
Alkalies	..	..	..	traces
Water and loss (H_2O)	..	..	..	3.61

The physical properties of the two qualities used for general building purposes vary a little, as will be seen on reference to the figures below.

WHITE QUARELLA STONE.

Specific gravity	..	..	..	2.27
Weight per cub. ft.	..	..	..	141 lbs.
Crushing resistance per sq. ft.	..	..	..	546.4 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	5.80

GREEN QUARELLA STONE.

Specific gravity	..	..	..	2.20
Weight per cub. ft.	..	..	..	137 lbs.
Crushing resistance per sq. ft.	..	..	..	437.5 tons.
Absorption, per cent. of its dry weight	..	..	..	4.70

In regard to its susceptibility to atmospheric attack, its chief weakness lies in the presence of salts of the alkaline

earths as subsidiary binding materials for the sand grains.

It should be noted that the Quarella Quarries were closed down in 1912, and up to the time of writing (1926) have not been reopened.

Red Wilderness Stone.—This stone is quarried out of the Old Red Sandstone deposits of the Devonian system. It is somewhat calcareous, and the sand grains of which it is composed are chiefly of quartz, with small quantities of felspar, tourmaline, and other minerals; mica is present also. The sand grains are bound by silica, with calcium carbonate and iron oxide as subsidiary binding materials. This stone is hard and of comparatively great strength, and it can be used for general building purposes. It is dull red in colour, medium-grained, and compact in texture. Speaking broadly, this stone weathers well, but if it is desired to use it in polluted atmospheres it should be carefully selected and fixed on its natural bed wherever possible. This stone is quarried at the Mitcheldean Quarries, Mitcheldean, Gloucestershire.

Its approximate chemical composition is as under:

Silica (SiO_2)	..	..	..	88.70
Aluminium oxide (Al_2O_3)	..	..	..	3.25
Ferric oxide (Fe_2O_3)	..	..	..	1.80
Ferrous oxide (FeO)	..	..	..	0.30
Manganese oxide (MnO)	..	..	..	0.10
Magnesium oxide (MgO)	..	..	..	0.11
Calcium oxide (CaO)	..	..	..	2.90
Sodium oxide (Na_2O)	..	..	..	0.31
Carbon dioxide (CO_2)	..	..	..	1.94
Water and loss (H_2O)	..	..	..	0.59

The chief physical properties are as follows:

Specific gravity	..	..	..	2.26
Weight per cub. ft.	..	..	..	141 lbs.
Crushing resistance per sq. ft.	..	..	..	695 tons (Kirkaldy)
Absorption, per cent. of its dry weight	..	..	..	2.10

Robin Hood Stone.—This is a light bluish-grey, fine-grained, and even-textured sandstone which occurs in the

Coal Measures series of the Carboniferous system. It is slightly micaceous, and the sand grains of which it is composed consist chiefly of quartz, and they are mainly silica-bound. If carefully selected, this stone proves an excellent one for general building work on account of its strength and free working qualities. It carries a sharp arris, and can be worked to a moderately smooth face. During weathering it is liable to change its colour to a light brown.

Its approximate chemical composition is as under:

Silica (SiO_2)	..	..	..	94.60
Aluminium oxide (Al_2O_3)	..	..	..	0.48
Ferric oxide (Fe_2O_3)	..	..	..	1.78
Magnesium oxide (MgO)	..	..	..	1.12
Calcium oxide (CaO)	..	..	..	1.54
Water and loss (H_2O)	..	..	..	0.53

The chief physical properties are:

Specific gravity	..	..	..	2.33
Weight per cub. ft.	..	..	..	145 lbs.
Crushing resistance per sq. ft.	..	..	..	574 tons (Rivington)
Absorption, per cent. of its dry weight	..	..	..	5.52

Roche Abbey Stone.—This stone is a member of the magnesian limestone class, and is quarried out of the Middle Permian deposits of the Permian system. It was formed, in all probability, in a similar manner to Anston stone (see p. 38), and is chiefly composed of small dolomite rhombs packed closely together in a matrix of the same material, and iron and aluminium oxides. In the stone mass are large numbers of minute irregular cavities, some of which are filled with calcite crystals and others with cryptocrystalline material of a yellowish colour. The current bedding in this stone is very often irregular. Its ground colour is cream, and there are numbers of brown ferruginous specks to be seen on the surface. In texture it is fine-grained, and a fresh fracture surface glistens, and has an appearance somewhat like lump sugar; on exposure it soon becomes dull.

This stone, like most of the magnesian limestones, is

rather soft. In the past it has been much used for general building purposes and for sculptured work, but under present-day conditions, especially in towns and cities, the use of this and the other magnesian limestones is not to be recommended for exterior work. This stone is quarried at the Bawtry Quarries, Bawtry, Yorkshire.

Its approximate chemical composition is as under:

Magnesium carbonate (MgCO_3)	..	..	..	39.4
Calcium carbonate (CaCO_3)	..	..	..	57.5
Iron and aluminium oxides (Fe_2O_3 and Al_2O_3)	..			0.7
Silica (SiO_2)	..	..	..	0.8
Water and loss (H_2O)	..	..	..	1.6

Its chief physical properties are given below:

Specific gravity	..	..	..	2.23
Weight per cub. ft.	..	..	..	139 lbs.
Crushing resistance per sq. ft.	..			250 tons (Rivington)
Absorption, per cent. of its dry weight				7.3

On weathering, especially in polluted atmospheres, it behaves very similarly to Anston and Mansfield stones, which see (pp. 40 and 90).

St. Bees Stones.—These stones are quarried out of the Bunter deposits of the Triassic system. As to the mode of formation of these stones and the other sandstones of the Bunter series, there seems to be some doubt. The two most favoured theories are: (*a*) That the sandstones were formed in a high lake “fed by streams flowing off a rocky desert country, from which sand was also frequently blown by strong winds into the lake”; and (*b*) that they were formed on a desert plain, “on to which sand was carried by rivers flowing from the northern mountains and from the surrounding hills; the further distribution and arrangement of this sand being accomplished by the action of the wind.” Microscopic examination of the sand in these stones shows the presence of wind-borne as well as water-borne sand grains, which indicates that one or other of these theories may be correct. The St. Bees stones are very slightly

calcareous, but the chief binding agent of the sand grains is silica. The sand itself is composed chiefly of quartz fragments, felspar, tourmaline, and mica fragments occurring in small quantities.

There are two qualities of St. Bees stone, St. Bees Red Freestone and St. Bees Head Freestone, the latter being the stronger stone. The former stone is bright red in colour, fine-grained and compact in texture, and it shows a slight bedding. The latter stone is dark red in colour, micaceous, and fine-grained and compact in texture. Both these stones are suitable for general building work, and the stronger stone may be used for engineering work also. The Red Freestone is quarried at the Bankend Quarries, near Bigrigg, Cumberland, and the Head Freestone at the Sandwith Quarries, near Whitehaven, Cumberland.

The approximate chemical composition of the two stones is given below:

ST. BEES RED FREESTONE.

Silica (SiO_2)	..	..	..	..	..	83.37
Aluminium oxide (Al_2O_3)	..	..	..	..	..	7.17
Iron oxide (Fe_2O_3)	..	..	..	..	..	1.77
Carbonic acid (H_2CO_3)	..	..	..	..	..	0.98
Magnesium oxide (MgO)	..	..	..	..	..	0.59
Calcium oxide (CaO)	..	..	..	..	..	0.59
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	3.73
Water and loss (H_2O)	..	..	..	..	..	1.80

(R. H. Hellon)

ST. BEES HEAD FREESTONE.

Silica (SiO_2)	..	..	..	..	..	85.20
Aluminium oxide (Al_2O_3)	..	..	..	..	..	7.00
Iron oxide (Fe_2O_3)	..	..	..	..	..	2.00
Carbonic acid (H_2CO_3)	..	..	..	..	..	1.00
Magnesium oxide (MgO)	..	..	..	..	..	0.30
Calcium oxide (CaO)	..	..	..	..	..	0.10
Potassium and sodium oxides (K_2O and Na_2O)	..	..	..	..	..	3.30
Water and loss (H_2O)	..	..	..	..	..	1.10

(R. H. Hellon)

The chief physical properties of these two stones are as follows:

ST. BEES RED FREESTONE.

Specific gravity	2.28
Weight per cub. ft.	142 lbs.
Crushing resistance per sq. ft. ..	393.1 tons (Stanger)
Absorption, per cent. of its dry weight	7.8

ST. BEES HEAD FREESTONE.

Specific gravity	2.17
Weight per cub. ft.	135 lbs.
Crushing resistance per sq. ft. ..	506.9 tons (Kirkaldy)
Absorption, per cent. of its dry weight	8.3

Storeton Stone (see Fig. 36).—This is a sandstone which occurs in the Keuper series of the Triassic system. It was formed, no doubt, in a very similar manner to the Hollington stones (see p. 76). The sand grains of which this stone is composed consist mainly of quartz, and they are chiefly angular and sub-angular in form. The natural binding material is silica. In colour this stone is pinkish-buff, and in texture it is medium-grained and compact. It carries a fair arris, and a moderately smooth surface can be prepared on it. For many years it has been employed locally, and as a stone for general building purposes it can be recommended. If this stone is to be used in a polluted atmosphere, then it should be carefully selected.

It is quarried at the Higher Bebington Quarries, Wirral, Cheshire.

Its approximate chemical composition is as under:

Silica (SiO_2)	95.48
Aluminium oxide (Al_2O_3)	3.06
Iron oxide (Fe_2O_3)	0.42
Magnesium and calcium oxides (MgO and CaO) ..	0.60
Water and loss (H_2O)	0.44

The chief physical properties are:

Specific gravity	2.23
Weight per cub. ft.	138 lbs.
Absorption, per cent. of its dry weight	4.8

Wealden Stone.—This is a ferruginous sandstone occurring in the Lower Greensand of the Lower Cretaceous series of



FIG. 36.—STORETON STONE
Note lines of current bedding

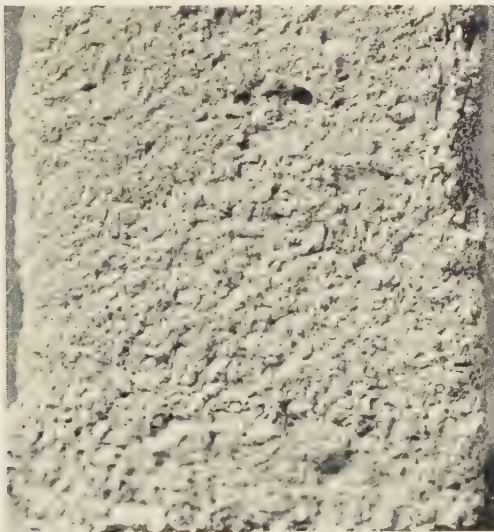


FIG. 37.—WELDON STONE
To face p. 106

the Cretaceous system. It is of lacustrine origin, having been deposited in the great Wealden freshwater lake. It is a fine-grained sandstone, light yellow in colour, and marked with brown specks, and it is somewhat soft in character owing to the fact that the amount of natural binding material is very small.

This stone has been used in buildings from very early periods, but for present-day work it cannot be recommended, especially in buildings which will be exposed to polluted atmospheres. Owing to the small amount of cementing material present, on weathering this stone is liable to very easy and rapid disintegration, as it falls away to a very fine powder (sand) which is easily removed by wind or rain. Decay is very marked along the lines of current bedding, forming deep furrows, and in the case of plain ashlar the tendency is to decay first at the joints. Its chief physical properties are as under:

Specific gravity	2.41
Weight per cub. ft.	150 lbs.
Crushing resistance per sq. ft. ..	279.2 tons (Kirkaldy)
Absorption, per cent. of its dry weight	10.4

Wealden stone is quarried at the Selsfield Quarries, East Grinstead, Sussex.

Weldon Stone (see Fig. 37).—This stone is quarried out of the Lincolnshire Limestone deposits of the Inferior Oolite series of the Jurassic system. It is buff to light brown in colour, with light brown markings. There are a number of small brown patches in the stone, and often quite a considerable quantity of small dendritic markings of black oxide of manganese. This stone is very shelly, the shelly detritus being small, and it is this material which produces a cellular structure in the stone. Current bedding is obvious, and along the beds the shelly matter occurs in layers. Weldon stone is markedly oolitic, and the matrix consists of crystalline calcite. It is a moderately hard stone, and it has been, and still is being, used as a building stone. Its cellular structure renders it liable to carry water from driving rain,

which will then penetrate through the stone to the interior, producing a damp structure.

This stone is quarried at the Weldon Quarries, Kettering, Northamptonshire.

Its approximate chemical composition is as under:

Calcium carbonate (CaCO_3)	..	..	..	..	94.35
Magnesium carbonate (MgCO_3)	..	..	..	..	3.55
Iron oxide (Fe_2O_3)	..	..	..	..	0.61
Aluminium oxide (Al_2O_3)	..	..	..	..	0.28
Silica (SiO_2)	..	..	..	..	0.08
Water and loss (H_2O)	..	..	..	..	1.13
					(Prof. Attfield)

Its chief physical properties are:

Specific gravity	..	..	..	..	2.42
Weight per cub. ft.	..	..	..	..	150 lbs.
Absorption, per cent. of its dry weight	..	..	..	..	4.8 (varies)

CHAPTER III

THE amount of marble used in the exterior of buildings is very small when compared with that of other stones, but its use in this direction is slightly on the increase. For interior work it is employed very largely, and it is also used freely for monumental and other memorial work. On this account it is considered advisable to mention briefly the chief of the British and foreign marbles.

In the trade the term "marble" is used somewhat loosely, and it covers any hard and compact limestone which is more or less coloured and capable of taking a good polish. In the geological sense these rocks cannot be considered as marbles. True marbles are metamorphosed limestones or dolomites, the original structure of which is changed by the action of heat under pressure, the origin of the heat being a deep-seated intrusion of molten igneous rock. Technically, the change is known as contact-metamorphism, and in this process the chemical composition of the rock is not changed, the calcium carbonate simply undergoing recrystallization with the formation of calcite. A true marble is, therefore, a granular aggregate of crystals of calcite or of calcium and magnesium carbonate, very compact in structure and containing a variety of coloured markings due chiefly to the presence of various iron compounds. The texture of the true marbles varies from fine to coarse-grained, the coarser grained being graded as a general rule as second quality.

The amount of water absorbed by the true marbles is very low, the average being 0.1 per cent. (lowest, 0.028 per cent.; and highest, 0.203 per cent.); and the moisture absorption factor of the compact limestones sold as marbles is much higher, varying between 4 and 5 per cent.

The specific gravity of the true marbles varies a little, the average being between 2.7 and 2.73, whilst that of the so-called marbles (compact limestones) is much lower: for instance, Hopton Wood stone has a specific gravity of 2.54.

Marble, like all natural substances, expands when exposed

to elevated temperatures, but it does not do this at a uniform rate under various temperatures, and there is always a certain amount of permanent set. On this account it is not possible to give an accurate coefficient of expansion.

Marbles are very slightly soluble in pure water, and more so in water containing carbon dioxide or sulphuric acid. Speaking broadly, they are less soluble in carbonic acid in a given time than the majority of the limestones. Tests made by G. P. Merrill ("Proc. U.S. National Museum," vol. 49, pp. 347-349) over a period of seventy days indicated that the average loss by solubility in a solution of carbonic acid sustained by marbles is 0.0083 per cent. (highest, 0.016 per cent.; lowest, 0.00056 per cent.), whereas in the case of oolitic limestones it is 0.52 per cent. (highest, 0.0308 per cent.; lowest, 0.017 per cent.). In a series of tests extending over three months the following results were obtained: Marbles, 0.014 per cent. of loss (highest, 0.026; lowest, 0.00077); limestones, 0.043 per cent. of loss (highest, 0.050; lowest, 0.032). Whilst these results are in favour of the marbles, the conclusion must not be drawn that this class of stone is highly suitable for use in exterior building work in towns and cities. There are other factors to be taken into consideration which in practice have proved that the marbles do not weather well, especially in the polluted atmospheres of towns and cities. It should be noted that all the marbles do not weather or corrode in like manner, and the same marble will exhibit differences in the mode of decay under varied conditions. The weathering of marbles may be divided into three main processes:

- (1) The solution of the surface.
- (2) Internal disintegration.
- (3) Curvature and fracture.

In the case of the first process the solution of the surface may be brought about by the action of comparatively pure water, but is accentuated by the presence in the water of carbon dioxide, sulphuric acid, or ammonium salts, such as

the sulphate. In the case of polished marbles solution of the surface means a loss of polish.

In regard to the second process, internal disintegration is due to some extent to the soaking in of water contaminated with carbon dioxide, sulphuric acid, or ammonium salts, and the consequent dissolving of the calcium carbonate and the final formation of calcium sulphate, which is brought to the surface in solution by capillary action, and there forms a hard covering when it crystallizes. The process of crystallization of calcium sulphate will also go on just under the immediate surface, and the change in molecular volume, with its consequent pressure, will push the crystalline grains of calcite apart. The solution of portions of the crystals of which the marble is composed will also weaken its structure.

With reference to the subject of curvature and fracture, Geikie considered that curvature is due to expansion caused by the freezing of water which is absorbed from rain. Whilst this may be one cause, others must not be overlooked; for instance, diurnal temperature changes will play a part. Careful experiments and observations have proved that marble which has been expanded by heat does not entirely contract to its original volume, and if one side of a piece of marble is raised to a higher temperature than the other and this process is repeated many times, then the side which is subjected to the greatest heat will be of greater volume than the other side, thus producing a bulging effect. Whatever the cause of the curvature or bulging of marble, there is no doubt that strains are set up which will produce minute fractures in the mass, and these, when once produced, will grow larger from time to time, especially during those periods when the marble is subjected to rain and frost.

Ashburton Marble.—Geologically this is not a true marble. Its ground colour is dark grey, and it is relieved by bright red and pale red veins, accompanied by white almond-shaped patches. It contains a fair amount of fossils, which consist chiefly of coral fragments. There is a darker variety of this marble, the veins of which are closer together, and the

fossils it contains are far less obvious. Ashburton marble is quarried at the Marble Quarries, near Ashburton, in Devonshire.

Ipplepen Marble.—Strictly speaking, this is not a true marble. It occurs in several varieties. One which is known as Grey Ipplepen has a light grey ground colour, which is marked by thin red veins and also crystalline veins of calcite. Another quality known as Red Ipplepen has a ground mass of deep red which is relieved by very light red veins and grey markings. There is yet another variety which possesses a dove-coloured ground streaked with veins of a flesh tint. These marbles are all slightly fossiliferous, but in many cases the fossils are very difficult to recognize. They are quarried at Ipplepen, near Newton Abbot, in Devonshire.

Purbeck Marble.—There are several varieties of this stone, and they are actually compact fossiliferous limestones and not true marbles. They vary chiefly in regard to their ground colours, one quality having a reddish-brown colour, another a greenish-grey, and another a light blue-grey. They are all hard and very distinctly fossiliferous, the chief fossil being that of a freshwater shell known as *Paludina*. In some specimens current bedding is more or less marked. This marble takes a good polish, which it does not retain for any great length of time. The Purbeck marbles are quarried out of the Upper Oolite beds near Swanage, in Dorsetshire.

Hopton Wood Marble.—This stone is not a true marble, but a compact limestone of the Carboniferous series. It is used largely as a building stone, but owing to the fact that it takes a fairly good polish, finds application as a decorative stone. A full description of this stone is given on p. 79.

Ogwell Marble.—There are at least three varieties of this compact limestone which are known commercially as marbles. One, known as Red Ogwell, has a dark brownish-red ground colour, which is figured with grey and white veins and also dark grey streaks. In this variety the fossils are not well defined. A light red quality of this marble is

quarried, the ground colour of which is not so deep as that of the variety just described; the markings are very similar, but the fossils are much more obvious. There is also a Grey Ogwell marble, the matrix of which is light grey, and it is distinctly fossiliferous. These marbles are quarried at the Ogwell Quarries, near Newton Abbot, in Devonshire.

Petitor Marbles.—These are also compact limestones which are wrongly called marbles from the geological point of view. They are all fossiliferous, and the chief varieties are: Yellow, which has a pale yellowish-grey ground, relieved by small splashes of yellow and thin pink veins; Grey, which possesses a ground of warm grey, marked with deep red veins and mottled with small black specks; and Pink, which has a light pink ground marked here and there with dark brown and red splashes, and largely with patches of yellow and grey. These marbles are quarried at St. Mary Church, in Devonshire.

Iona Marble.—This stone can be placed among the true marbles. It is a metamorphosed dolomitic limestone of the opicalcite type, and it has a beautiful pale green or pure white ground, which is relieved by markings and veins of light green, or at times of deep bluish-black or white. It is a very serviceable marble for decorative and ecclesiastical work. This marble is quarried in the Isle of Iona, Argyllshire.

Irish Marbles.—There are several varieties of Irish marble, among which may be mentioned Irish Green, or Connemara Green, and Irish Black. The former can be considered as a true marble, but petrologically it is known as an opicalcite, and it is of a serpentinic nature. Actually it is a metamorphosed limestone of the dolomitic type, which has originally contained silica (SiO_2). The latter is a compact limestone of the Carboniferous series.

Irish Black has a deep, pure black ground, which is at times relieved by somewhat cloudy markings of a dark bluish-grey, these being due to fragments of stems of encrinites. It takes a very good polish, and is largely used

for ornamental work. Connemara Green has a delicate to light sage-green ground, is in places semi-translucent, and is relieved with whitish markings and veins of dolomite or calcite. The Black marble is quarried near Spring Hill, Co. Carlow, and the Green marble near Clifden, Co. Galway.

Campan Marble.—There are several varieties of this French marble, all of which are obtained from the Campan Valley, Hautes Pyrenees. Three of the best known are described below.

Campan Vert.—This variety has a light green ground, which is relieved by small veins of white or grey, and spotted with tiny almond-shaped markings. It is slightly fossiliferous.

Campan Rose.—The ground colour of this quality is dull red or reddish-brown, and it is marked with veins and spots some of which are pink, others dark red, and others almost white. Some qualities of this marble are marked with green veins.

Campan Melange.—This quality is very much more distinctive in character than the Campan Vert, for in addition to its beautiful green ground and somewhat similar markings, there are bands of darker green, brown, and pink.

Languedoc Marble.—This is a semi-crystalline marble, the ground of which is bright red in colour, and it is marked with grey and pink veins and in places with patches of white calcite. It is useful for decorative work in which contrast is desired. The quarries are situated at Caunes, in the Aude Department, and also Alais, in the Department of Gard.

Jaune Lamartine Marble.—This rock is a true marble which has been formed by the metamorphosis of limestones of the Jurassic system. It has a bright yellow ground which is relieved by an abundance of fine anastomosed markings of red and grey. It is an excellent marble for interior decorative work, and it is obtained from the Vaux Quarries, near Mollinges, in the Department of Jura.

St. Anne Marble.—This is a fossiliferous marble, and it has a medium blue-grey ground relieved by a very large

number of irregular veins of various widths, and splash-like markings which vary in size; the colour of these markings and veins is very light grey. The general aspect of the marble is that of very small light clouds on a dark background. It takes a high polish, and is used chiefly for interior decoration. The quarries are situated near Gougny, in the Province of Namur.

Belgian Black Marble.—This is a very fine black marble, uniform in colour and close in texture, which takes a high polish, and is employed for decorative purposes. It is very hard and difficult to work, and is therefore expensive, but in spite of this, is used to a fairly large extent. The quarries are situated near Mazy, in the Province of Namur.

Rouge Marble.—There are a number of varieties of this marble, and that known as Rouge Griotte is accepted as the best quality. This marble has a ground colour of dark brownish-red with bluish-grey cloud-like markings relieved with veins of almost clear white. It is quarried out of rocks which belong to the Devonian system at the Vodelee Quarries, in the Province of Namur.

Blue Belge Marble.—This is a crystalline marble, the ground colour of which is deep blue-black. It is relieved by narrow veins of white and light grey intermixed with others of a bluish-grey shade. A very good polish can be prepared on this marble, and it is used for interior decoration. It is quarried out of rock occurring in the Carboniferous system at Bioulx, in the Province of Namur.

Rouge Royal Marble.—This is a fossiliferous marble occurring in the Devonian system, and it has a ground colour of light reddish-brown, which is relieved by irregular veins and splash-like markings, some being nearly white, and others light grey or dark brown. It is employed for interior decorative purposes and in sanitary engineering. The quarries are situated at Vodelee, in the Province of Namur.

Rouge Imperial Marble.—The ground colour of this marble is dark reddish-brown, and it is marked with a few eccentric and small to very large cloud-like patches of a light to

medium bluish-grey colour. It takes a fairly good polish, and is employed for interior decoration. Like others of the Rouge marbles it is obtained from the Vodelee Quarries, in the Namur Province.

Rouge Byzantine Marble.—This quality of Belgian marble has a ground of a pinkish shade which is marked with irregular veins, some of which are very wide, and their colour varies from white to medium grey, and even pink. There are also large blotches of dark and light grey intermixed with irregular vein-like markings of reddish-brown. This marble is quarried in the Namur district.

Emperor's Red, or Encarnado.—This is a slightly fossiliferous marble possessing a pale red ground which is marked with white and pink veins. It is useful for interior decorative work, but must not be employed in exteriors, as it easily suffers from atmospheric attack. This marble is obtained from the Pedra Furada Quarries, Pero Pinheiro, Estremadura.

Vidraco Marbles.—There are two qualities of this marble known commercially as No. 1 and No. 2. They occur in the Upper Jurassic system, and are both fossiliferous. The No. 1 quality has a ground colour of pale bluish-fawn, which is relieved by thin veins of a reddish-brown colour, whilst the No. 2 quality is of a dark fawn marked by thin veins, the colour of which is deep red. These marbles are used largely for interior decorative work, and have found application for exterior building. They are quarried at the Macerio Quarries, Pero Pinheiro, Estremadura.

Norwegian Marbles.—These marbles vary only in the ground colour and the markings, the texture of all qualities being practically alike. A noteworthy feature of some varieties is their freedom from veins.

Brèche Rosé has a pale rose-pink ground which is marked with patches of white, and occasionally with pale green veins.

Leifset Gloire possesses an almost white ground, which is relieved by pink and green bands.

Gjelleboek is characterized by a grey ground tinged with brown and green, and

Norge Clair is practically pure white.

The Norwegian marbles are quarried chiefly at the Skjerstadt and Vel fjords.

Greek Cipollino.—The ground of this marble is pale green with a greyish hue, and it is marked by darker green wavy bands varying from narrow to broad. Like the Swiss Cipollino, it has been used in exteriors as well as interiors, and appears to serve both purposes quite well. It is quarried in the Isle of Eubœa.

Tinos.—This is another well-known Grecian marble included in the class of ophicalcites. It has a ground of a bright deep green colour, which is marked by a very close network of veins of various lighter shades of green, and also white. Apparently this marble behaves well in exterior work, and it is used also for interior decoration. The quarries are situated in the Isle of Tinos.

Swedish Green.—This rock is a metamorphosed dolomite, and it has a pale green to almost white ground, marked with whitish veins and mottling. It is used largely for interior decorative work in almost all European countries. The quarries are situated at Norrköping, Östergötland.

Swiss Cipollino.—This is a crystalline marble quarried out of the rocks of the Jurassic system. The ground colour is pale green, and it is relieved by dark green veins, usually straight, and sometimes wavy. It has been used for exterior work as well as for interior decoration on the Continent, and it is to be seen in some ecclesiastical and public buildings in this country. It is quarried at the Saillon Quarries, Canton Valais, in Switzerland.

Arni Vein Marble.—This is a true marble, possessing an almost white ground, which is relieved by irregular veins of a greyish tint. It is an important marble, which finds considerable application for interior decoration both in this country and on the Continent. The quarries are at Arni, Carrara, Tuscany.

Rhondona Marble.—This is a brecciated marble composed of fragments of earlier metamorphosed limestones having mainly a white ground stained a bright green, dark purple, or pink, and embedded in a matrix of a later marble, usually of a purple colour. It is a very beautiful marble for decorative purposes, and it has been used for ecclesiastical work, and for interior decoration of public buildings. The quarries are near Pretrasanta, Tuscany.

Verde di Genova Marble (Genoa Marble).—This is a serpentinous rock, having a brecciated structure, and its ground colour is a beautiful dark green which is figured with veins of a lighter green and others of white. It is eminently suitable for all decorative purposes, and it has been employed for exterior work. As, however, serpentines weather badly, its use for the latter purpose is not to be recommended. The quarries are situated at Pietra Lavezzaria, near Genoa.

Statuary Marbles.—This is a group of Italian marbles used mainly for statuary purposes. The members of this group are true marbles, and the best qualities are pure white, and practically free from markings; their texture is usually fine, and they are highly crystalline. There are second qualities, the pure white ground of which is marked in places by light bluish-grey cloud-like patches, or veins of a greyish colour. Both qualities take a high polish, which soon disappears on exposure to atmospheric conditions. The chief members of this group are:

Altissimo (White Statuary).—A very pure white marble.

Parona (White Statuary).—Similar in colour to Altissimo, but slightly coarser in texture.

Porracci (White Statuary).—Not of such a pure white as the two varieties just mentioned.

Parona (Statuary).—This variety is marked with veins of a greyish colour.

Tulanto (White Statuary).—A marble with a pure white ground, sparsely marked with grey veins.

CHAPTER IV

WHILST the granites are valuable and important building stones, they are not used to anything like the extent that the limestones and sandstones are. This is due in a large measure to their hardness and the difficulty presented in working, and the consequent high cost. However, as far as space will allow, a brief description of the chief British granites is given in the following pages.

The principal quarries in Great Britain from which granite is obtained are situated in Aberdeen, Kirkcudbrightshire, and Cornwall.

If the typical granites are considered it will be seen that there is a general uniformity of character throughout their mass, but it must not be forgotten that there are instances of variation which in some cases is of a very pronounced character.

Cheesewring Granite.—This rock is a muscovite-biotite granite. Its colour is a mixture of pink, red, and grey, and it is rather coarse in texture. In addition to felspar, quartz, and mica, it contains andalusite as an accessory constituent. Its general use is found in engineering work, but it has been used in monumental work also.

Cheesewring granite is quarried out of the Bodmin granite mass at the Cheesewring Quarries, near Liskeard, Cornwall.

The approximate physical properties of this granite are given below:

Specific gravity ..	..	..	..	..	2·70
Weight per cub. ft. ..	..	..	..	..	169 lbs.
Crushing resistance per sq. ft. ..	..	..	..	..	1,441 tons
Absorption, per cent. of its dry weight ..	..	..	..	..	0·16

Colcerrow Granite.—This is a muscovite-biotite granite. The ground colour is light grey speckled with fairly large masses of dark grey and smaller ones of black; it contains porphyritic crystals of felspar, many of which are 5 inches in length, also white and black micas and tourmaline. The felspar is in the form of orthoclase. The texture of this

stone is rather coarse. It is used for engineering work generally, and it is quarried at the Colcerrow Quarries, St. Austell, Cornwall.

The physical properties of this granite are:

Specific gravity	2.70
Weight per cub. ft.	166 lbs.
Crushing resistance per sq. ft. .. .	1,337 tons
Absorption, per cent. of its dry weight .. .	0.18

Correnie Granite.—This stone is a biotite granite, its colour is bright salmon to a warm red tint, and it is medium-grained. The pinkish colour in this stone is due to crystals of felspar, which are mostly irregular, and it should be noted that it contains very little mica.

Correnie granite finds its use in engineering and building work, and it has also been used in technical machinery, and for decorative work.

It is quarried at the Correnie Quarries, near Alford, Aberdeenshire.

The approximate physical properties of Correnie granite are as under:

Specific gravity	2.58
Weight per cub. ft.	160 lbs.
Crushing resistance per sq. ft. .. .	1,301 tons
Absorption, per cent. of its dry weight .. .	0.40

When this granite starts to decay little depressions or cavities form, generally along the arrises.

Creetown Granite.—This stone is a biotite granite. It is light grey in colour, and has a beautiful clean white appearance when freshly axed. It takes on a good polish, and is used for architectural work, also for engineering work generally. It is medium-grained, and is quarried at the Kirkmabrede Quarries, Creetown, Scotland.

The physical properties of Creetown granite are as follows:

Specific gravity	2.73
Weight per cub. ft.	169 lbs.
Crushing resistance per sq. ft. .. .	1,630 tons.
Absorption, per cent. of its dry weight .. .	0.24

Dalbeattie Granite.—This is a quartz-diorite or tonalite, and although a plutonic rock, is not a true granite. It varies in colour from grey to buff, and it has a pinkish shade, due to the crystals of felspar. The chief minerals contained in it are white oligoclase, felspar, quartz, orthoclase, black mica, and hornblende. It is employed for building work, and it is quarried at the Granite Quarries, Dalbeattie, Kirkcudbrightshire, Scotland.

The approximate physical properties of this stone are as follows:

Specific gravity	2.89
Weight per cub. ft.	179 lbs.
Crushing resistance per sq. ft.	905 tons
Absorption, per cent. of its dry weight	0.18

Dancing Cairns Granite.—This is a muscovite-biotite granite, its ground colour is light grey, and it is thickly speckled with black and glistening crystals. It contains quartz, black and white micas, and felspar. All the crystals are comparatively small, and the rock itself is medium-grained. It is employed in building work, but chiefly in engineering.

This stone is quarried at the Dancing Cairns Quarries, near Aberdeen, Aberdeenshire. The approximate physical properties are given below:

Specific gravity	2.74
Weight per cub. ft.	170 lbs.
Crushing resistance per sq. ft.	850 to 900 tons
Absorption, per cent. of its dry weight	0.12

De Lank Granite.—This is a biotite-muscovite granite, and its colour is light greenish-grey. The felspar in this stone is almost white in places, with a general inclination to be slightly pinkish, and it is well speckled with biotite, which is somewhat coarser than that in the Kernnay granite. This stone is employed for engineering work generally, and it is used on occasion in the building industry.

De Lank granite is quarried from the De Lank Quarries, near Bodmin, in Cornwall.

The approximate physical properties are:

Specific gravity	2.65
Weight per cub. ft.	163 lbs.
Crushing resistance per sq. ft.	1,170 tons
Absorption, per cent. of its dry weight	0.18

Dyce Granite.—This is a biotite granite; its colour is dark greyish-blue, and its texture is fine, and there is a tendency to show a laminated arrangement of its constituent minerals. It is employed for all sorts of structural work at home and abroad; it is also used for interiors of buildings.

This stone is quarried at the Dyce Quarries, Dyce, Aberdeenshire. The approximate physical properties are:

Specific gravity	2.63
Weight per cub. ft.	165 lbs.
Crushing resistance per sq. ft.	1,105 tons
Absorption, per cent. of its dry weight	0.18

Kemnay Granite.—This rock is a muscovite-biotite granite, the colour of which is light silvery-grey, and it is speckled with black mica. In texture it is medium-grained, and it is capable of taking on a good polish. It is employed in the building industry and largely in engineering work, and it has been used in the construction of memorials. In building work it is generally used in cases in which contrast is required. It is a bright-looking stone, and it weathers very well indeed.

Kemnay granite is quarried at the Kemnay Quarries, near Aberdeen, Aberdeenshire.

Its physical properties are as follows:

Specific gravity	2.58
Weight per cub. ft.	160 lbs.
Crushing resistance per sq. ft.	1,212 tons
Absorption, per cent. of its dry weight	0.21

Lamorna Granite.—This is a muscovite-biotite granite. Its colour is grey, but the large porphyritic crystals contained in it give it a green tint; this tint is usually due to the presence of minute scales of chlorite. This stone is chiefly employed for engineering work, but it can be used for

building work also. It is quarried at the Lamorna Quarries, near Lamorna Cove, Penzance, Cornwall.

The physical properties of this granite are:

Specific gravity	2.70
Weight per cub. ft.	167 lbs.
Crushing resistance per sq. ft. .. .	1,100 tons
Absorption, per cent. of its dry weight .. .	0.18

Mountsorrel Granite.—This stone is a hornblende-biotite granite. There appears to be several varieties of this stone, one being a dark grey in colour with paler felspar crystals scattered rather sparingly throughout its mass. It also contains small crystals of quartz of a bluish-grey colour, and patches of dark hornblende. Another darker variety is similar in structure, but the ground colour is dark red-brown, the porphyritic crystals of felspar being somewhat paler. The latter variety is largely employed in building construction, for which purpose it seems to be well suited. It is very hard and fine-grained. The lighter variety, although it takes on a good polish, is not used much for building work, but it finds employment in engineering work generally.

Mountsorrel granite is quarried at the Mountsorrel Quarries, near Sileby, Leicestershire.

The approximate physical properties of this stone are:

Specific gravity	2.65
Weight per cub. ft.	165 lbs.
Crushing resistance per sq. ft. .. .	2,086 tons
Absorption, per cent. of its dry weight .. .	0.13

Penryn Granite.—This stone is a muscovite-biotite granite. It is light grey or greenish-grey in colour, speckled with black, and it is coarse in texture. Felspar crystals occur in this rock which measure between $\frac{1}{2}$ to $\frac{3}{4}$ inch in length, and they are associated with grey quartz, white mica (muscovite), black mica (biotite), and also tourmaline. The Penryn granites have been very extensively employed for engineering and building purposes.

There are two qualities of Penryn granite. One is a

light grey, fairly coarse-textured stone, which is quarried at the Penryn Quarries, Penryn, Cornwall, and its approximate physical properties are as under:

Specific gravity	2.62
Weight per cub. ft.	164 lbs.
Crushing resistance per sq. ft.	1,250 tons
Absorption, per cent. of its dry weight	0.12

The other quality is light greenish-grey in colour, and is medium-grained. This stone is quarried from the Carnsnew Quarries, Penryn, Cornwall, and its physical properties are:

Specific gravity	2.65
Weight per cub. ft.	166 lbs.
Crushing resistance per sq. ft.	1,435 tons
Absorption, per cent. of its dry weight	0.10

Both qualities take a good polish.

Peterhead Granite.—This is a biotite granite; its colour is red or dark flesh tint, and it is moderately coarse in texture. There is also another quality which is bluish-grey in colour and fine in texture which is quarried from the Rora Quarries, near Peterhead. This variety is not so popular as the red Peterhead stone, but it is used considerably. The red Peterhead granite, which takes on a good polish, is used largely for engineering, building, and monumental work all over the world. It is quarried at the Red Granite Quarries, Peterhead, Aberdeenshire.

The approximate physical properties of this stone are:

Specific gravity	2.53
Weight per cub. ft.	158 lbs.
Crushing resistance per sq. ft.	1,469 tons
Absorption, per cent. of its dry weight	0.26

Bluish-Grey Quality.—The physical properties of this quality approximate those of the red Peterhead granite.

Princetown Granite.—This stone is a tourmaline-biotite granite; it is light grey in colour, and it contains an abundance of dark mica and pinkish felspar; sometimes it is distinctly porphyritic. There are two qualities of this granite, one being coarse in texture and the other medium.

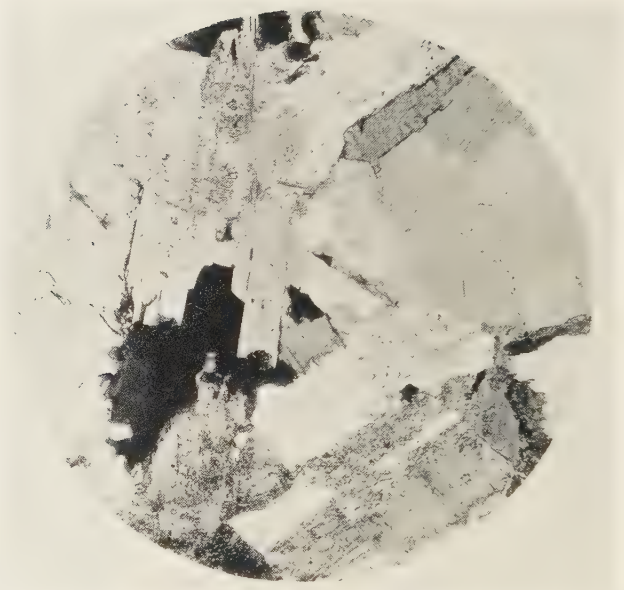


FIG. 38.—RUBISLAW GRANITE
Section magnified 30 diameters



FIG. 39.—RUBISLAW GRANITE
Section magnification 5

This granite is employed mainly for engineering work, and has entered into the construction of many large and important works.

The approximate physical properties of the coarse granite are as under:

Specific gravity ..	..	..	..	..	2.62
Weight per cub. ft.	..	..	..	..	162 lbs.

and the approximate physical properties of the medium-textured quality are given below:

Specific gravity ..	..	..	..	..	2.65
Weight per cub. ft.	..	..	..	..	166 lbs.

This stone is quarried at the Princetown Quarries, Dartmoor, Devonshire.

Ross of Mull Granite.—This is a biotite-microcline granite, the colour of which is salmon-pink to warm red. In texture it is coarse, and some of the quartz crystals contained in it are well defined. It carries a good polish, and is employed for engineering and building work. This stone is quarried at the Granite Quarries, Ross of Mull, Argyllshire.

The approximate physical properties of this stone are as under:

Specific gravity ..	..	..	..	..	2.80
Weight per cub. ft.	..	..	..	..	175 lbs.

Rubislaw Granite.—This is a muscovite-biotite granite, grey in colour and fine-grained, which takes a high polish and is extremely durable. It contains white and black micas, the latter being more abundant, together with crystals of felspar and quartz. In constructional engineering work it is used to a very large extent, and considerable quantities have been used for building purposes, especially in Aberdeen.

The quarries from which this stone is obtained are the Rubislaw Quarries, Aberdeen, Aberdeenshire.

Its approximate physical properties are as under:

Specific gravity ..	..	..	..	..	2.60
Weight per cub. ft.	..	..	..	..	162 lbs.
Crushing resistance per sq. ft.	..	..	..	..	1,288 tons
Absorption, per cent. of its dry weight	..	..	..	..	0.10

Figs. 38 and 39 illustrate the appearance of this granite when a section is examined by the microscope.

Sclattie Granite.—This is a muscovite-biotite granite. It is generally light grey in colour, but the shade varies to a darker tint according to the part of the quarry from which it is obtained, and it possesses a close texture. Road engineers use large quantities of this stone, and it is employed in the building industry. This stone is quarried at the Sc lattie Quarries, near Aberdeen, and its approximate physical properties are as follows:

Specific gravity	2.56
Weight per cub. ft.	160 lbs.
Crushing resistance per sq. ft. ..	849 tons
Absorption, per cent. of its dry weight ..	0.10

Shap Granite (see Fig. 40).—This is a biotite granite, and it contains large flesh-coloured orthoclase (potash felspar) crystals, which impart a warm rich tinge to the rock; these crystals are sometimes 1 inch in length. Other minerals found in this granite are: black mica (biotite), magnetite, apatite, sphene, and naturally a large quantity of quartz. It admits of a very fine polish, and the polished surface of Dark Shap granite viewed from a short distance appears brownish-red, speckled with black and light grey. There are two different shades in the granite obtained from the Shap Quarries, known in commerce as “Light Shap” and “Dark Shap.” The Dark Shap granite is pink and brown in colour and coarse in texture, and the Light Shap granite is light pink in colour and its texture is also coarse. Both kinds are quarried at the Wasdale Fell Quarries, Shap, Westmorland. These granites are employed largely for building and engineering work.

The approximate physical properties of these granites are as follows:

Specific gravity	2.57
Weight per cub. ft.	160 lbs.
Crushing resistance per sq. ft. ..	1,200 tons
Absorption, per cent. of its dry weight ..	1.30



FIG. 40.—SHAP GRANITE
Note the large feldspar crystals

To face p. 126

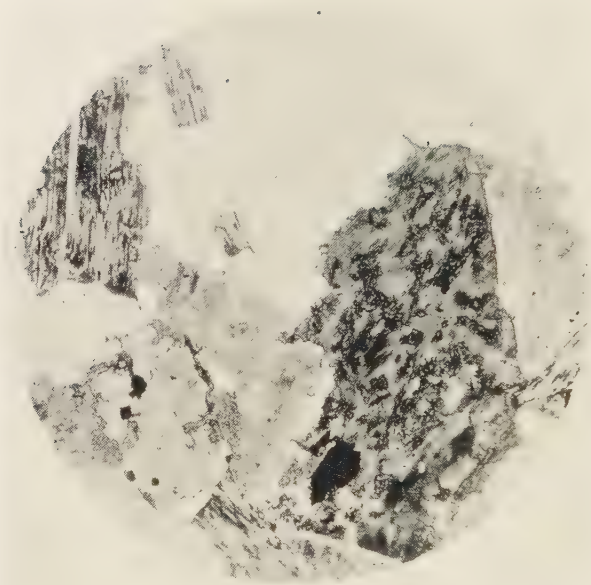


FIG. 41.—SHAP GRANITE
Section magnified 30 diameters



FIG. 42.—SHAP GRANITE
Section magnification 5

Figs. 41 and 42 illustrate the appearance of this granite when a section is examined by the microscope.

Tor Granite.—This is a biotite granite. It is light grey in colour, with a pinkish tinge, and it is medium-grained in texture. For building and engineering work it is a useful stone, having been used in a number of important works. It is quarried at the Tor Quarries, Merrivale, Devonshire.

The approximate physical properties of this granite are:

Specific gravity ..	..	..	..	..	2·62
Weight per cub. ft.	..	..	..	..	163 lbs.

Tyrebeggar Granite.—This is a biotite granite, the colour of which varies from grey to a bright pink, and in texture it is fine-grained. It is extensively employed for decorative and building work. This stone is quarried at the Tyrebeggar Quarries, Aberdeenshire.

The approximate physical properties of this granite are as follows:

Specific gravity ..	..	..	..	..	2·74
Weight per cub. ft.	..	..	..	..	170 lbs.

CHAPTER V

"Nature is ever making signs to us, she is ever whispering to us the beginnings of her secrets; the scientific man must be ever on the watch, ready at once to take hold of Nature's hint, however small; to listen to her whisper, however low."—M. FOSTER.

Never let it be forgotten that STONE IS A CHEMICAL; and also it is frequently THE LITTLE THINGS THAT MATTER.

DURING recent years the decay of building stones has become a matter of concern, and in 1923 it was considered of such importance that a Government Committee (the Stone Preservation Committee) was formed to investigate this subject, and that of preservation, in all its aspects.

Speaking broadly, decay in building stones is brought about by (*a*) physical processes, and (*b*) chemical processes, and in most cases, if not all, the two processes work in conjunction. To these must be added (*c*) conditions set up in the stones during the process of geological formation—for instance, joints, cleavage planes, and current beddings; and (*d*) structural defects in the building in which the stone is used, such as settlements; opening up of joints; the cracking of blocks of stone due to pressure or other causes; no weatherings or badly made weatherings on projections, causing the lodgment of water; badly made damp-proof courses, or the absence of these; badly designed or carelessly built roofs, especially flat ones; badly designed or badly built balconies; bad bricks and mortar in those buildings in which stone is used as dressings; non-weather-proof casements; improperly constructed flashings; badly designed members in the enrichments, especially those which allow the lodgment of water; defective gutterings and fall pipes. Naturally the mineralogical character, chemical composition, and physical structure of the stone will influence the rate and extent of decay during any period of time.

Of the physical or mechanical processes the following may be mentioned:

(a) Solution.

(b) Pressure brought about by changes in molecular volume due to the formation and crystallization of new chemical compounds.

(c) Attrition, whilst the stone is dry or wet, produced by wind, wind-blown grit, hail, and heavy rains.

(d) Diurnal variations in temperature, producing expansion and contraction.

(e) Pressure produced by the expansion of water due to freezing.

(f) Mechanical action (pressure) produced by the growing roots or hyphæ of plants.

Among the chemical processes may be mentioned:

(a) The action of acids, including certain plant acids.

(b) The action of chemical salts.

(c) Hydration.

(d) Oxidation.

(e) Deoxidation.

(f) Action of bacteria.

To assist in understanding these processes, it is necessary to carefully study such matters as surface tension, interfacial tension, adsorption, and also ionization.

The chief carriers of the substances which bring about chemical reactions are rain and the atmosphere, the latter often in the form of wind. Rain-water contains various gases dissolved in it, among which may be mentioned carbon dioxide and sulphur dioxide, and it also contains chemical salts, such as ammonium sulphate and ammonium chloride. In polluted atmospheres, and especially in the neighbourhood of large manufacturing centres, the following deleterious substances may occur: Soot, ammonium sulphate, ammonium chloride, free hydrochloric acid, free sulphuric acid, carbon dioxide; and in the case of wind, road detritus such as grit and horse manure.

Suspended in the atmosphere there are very considerable numbers of tiny solid and liquid particles. The origin of some of these is the fine dust caught up by the wind, but

the chief source is the combustion of fuel in the factory furnace and the domestic fire-grate. It has been shown by Aitken¹ that as many as 300,000 dust particles per c.c. of air may be found in the neighbourhood of industrial areas, whilst the atmosphere over uninhabited spaces of country will contain only a few hundreds per c.c. In this connection it is interesting to note that during the winter months in London the average limit of visibility on a "clear" day does not exceed half a mile, which corresponds approximately to 200,000 particles per c.c. of air. The significance of this will be clear to the reader when it is pointed out that a large number of these particles are liquid, or partially liquid (dust particles surrounded by a film of liquid), and contain sulphuric acid, which renders them hygroscopic and assists in the formation of fog. The stability of a fog produced in an industrial area is increased by the fact that the sulphuric acid dissolved in the liquid particles retards their evaporation, and this is assisted by the formation of films of tarry oil on the particles due to the presence of coal smoke. Now, these particles are in rapid motion (Brownian motion), and when they come into collision with solid substances, say the stone walls of a building, they condense on the surface, forming a dirty, acid deposit, which not only stains the stone, but assists in its decay. It should be noted that the cooler the surface, relatively, the greater will be the amount of condensation within certain limits.

TABLE I.

<i>Year.</i>	<i>Locality.</i>	<i>Soot Fall (Tons per Square Mile per Year).</i>
1912 ..	Leeds: Industrial centre	539
	Suburban area	26
1910 ..	London: Centre of city	426
	Average for whole Metropolitan area	248
1910-11	Glasgow: Centre	820
1911-12	Pittsburg	1,031

¹ See "Fourth Report of Colloid Chemistry," H.M. Stationery Office, London.

The table¹ on opposite page (No. 1), showing the annual soot fall in tons per square mile in various cities, will no doubt prove of interest.

In Leeds there are 35,000 tons (approximately) of soot, etc., discharged into the atmosphere annually.

It should be borne in mind that soot is a mixture of various substances, and its character differs to a large extent according to the conditions under which coal is burnt, and the kind and variety of coal. Liquid fuel produces soot also, and it varies to some extent in its character. All classes of soot show an acidity figure which is apparently due to the presence of free mineral acid, and this acidity varies somewhat, as the following table will show.

TABLE II.

<i>Domestic Soot (Coal Fire).</i>	<i>Industrial Soot (Coal Fire).</i>	<i>Industrial Soot (Liquid Fuel).</i>
0.52 per cent.	0.59 per cent.	0.68 per cent.

Soot contains a considerable amount of free carbon, and also smaller quantities of other bodies, among which are phenols, aromatic hydrocarbons, ammonium sulphate, and ammonium chloride.

Whilst dealing with the matter of polluted atmospheres and soot, attention should be called to the fact that quite a large number of people are under the impression that the suppression of smoke by the introduction of smokeless fuel will remove all the deleterious substances from the atmosphere. This is not the case, for coke (smokeless fuel) contains sulphur, and on combustion sulphur dioxide is formed, which will eventually be converted into sulphuric acid by oxidation and hydration whilst it is in the atmosphere. Coal gas, another smokeless fuel, contains a small quantity of sulphur compounds, and unless these are removed, a similar result will be obtained when this substance is burned.

¹ See "Fourth Report of Colloid Chemistry," H.M. Stationery Office, London.

In any case, whatever smokeless fuel is used, the chief waste product of combustion, carbon dioxide, is always formed, and this substance is an active one in regard to the decay of stone. Another point which must not be lost sight of is that the increase in petrol motor traffic means an increase in the amount of carbon dioxide and sulphur dioxide in the atmosphere, especially in that of large cities and towns.

The amount of atmospheric pollution is a variable quantity, changing according to the district, the season of the year, the time of the day, the condition of the weather, and so on. In places some distance from manufacturing centres the atmosphere may be only slightly polluted for quite a long time, and then become for a short period badly polluted, according to the direction of the wind; and often these periods are sufficiently long to make themselves felt in regard to the matter of decay of stone.

Table No. 3 will give the reader some idea of the variation in atmospheric pollution, and also of the rainfall at London, Manchester, Rochdale, and Southport.

TABLE III.—ANNUAL TOTALS.¹

	<i>Inches.</i>	<i>Tons per Square Mile.</i>					
		<i>Total Solids.</i>	<i>Soluble Matter in Total Solids.</i>	<i>Insoluble Matter in Total Solids.</i>	<i>Included in Soluble Matter.</i>		
					<i>SO₄.</i>	<i>Cl.</i>	<i>NH₄.</i>
LONDON:							
Meteorological Office	25·00	340·99	164·66	176·32	49·81	23·77	2·14
Wandsworth Common	15·74	225·6	104·77	120·83	36·91	16·56	2·39
Golden Lane	27·16	388·89	177·57	211·32	75·94	23·23	8·59
ROCHDALE	38·00	672·92	179·93	492·98	—	—	—
MANCHESTER	34·10	543·02	214·27	328·75	89·30	33·12	3·73
SOUTHPORT	27·63	170·33	127·05	43·28	33·71	30·25	13·71

¹ Calculated from figures published by the Meteorological Office.

It should be noted that the portion of the soluble matter which contains the SO_4 , Cl , and NH_4 ions very materially assists in the process of decay of the limestones, dolomites, and of those sandstones which contain a comparatively large amount of calcium carbonate or calcium and magnesium carbonates as subsidiary binding agents. The crystallization of the salts of which these ions constitute a part may at times cause disintegration, and the author has come across cases in which sandstone has got into a state of decay owing to the crystallization of ammonium sulphate, derived from the atmosphere, rupturing the silica matrix and pushing the sand grains apart.

The process of decay is assisted by an action between the salts contained in the soluble matter and the stone material, and this is primarily one of decomposition, with the formation of new compounds, and finally the crystallization of these salts, or, owing to their great solubility in water, their being washed away entirely. This latter process will in time remove a good deal of the original stone substance, and this weakens its structure.

It must not be thought that the insoluble matter is an inactive agent as regards the decay of stone; rather does it assist, for if it contains tarry, or sooty, or other material of a somewhat sticky nature, it will eventually, especially when assisted by soluble salts produced by the action of deleterious substances on the stone, form a hard surface which sometimes becomes almost as smooth as glass, although very black, and which eventually results in scabbing or exfoliation. As will be seen in another part of this chapter, tar itself is liable to produce trouble due to possible action between some of its ingredients and the stone substance.

The prevalent direction of the wind, its velocity, and its humidity, and also the amount of rainfall, especially during fairly high winds coming from a district the atmosphere of which is polluted, will all add their quota to the cause of decay of stone. From these remarks it will be seen that it does not follow that a stone structure situated in a com-

paratively unpolluted atmosphere (as determined by the aid of a deposit gauge, etc.) will not suffer from decay via the atmosphere. Carefully observed cases have shown that situations as far removed as thirty-five miles away from a polluted atmosphere (say one caused by the presence of chemical works or heaps of pit waste which have become ignited) are not free from danger. Several cases of decay in different parts of the country caused by these conditions are known to the author. Owing to incomplete meteorological observations it is not an easy matter to give complete sets of figures, but the following data relative to the Southport district may be of some interest. Approximately 16 per cent. of the annual winds are in a south-easterly direction, and when the wind is in this direction 5.78 inches of rain has fallen during the same period. The average velocity of the wind is forty-five miles per hour, and it comes from a direction which will cause it to pass over the manufacturing centres of St. Helens and Warrington, both of which produce very polluted atmospheres, and the former of which is approximately twenty-three miles and the latter thirty-eight miles from Southport. It will be seen in this case that a wind travelling at a velocity of forty-five miles per hour will quite easily carry, in a very short time, a certain amount of pollution from the atmosphere of the towns just mentioned, and a certain percentage of this will be washed out by the rain, and therefore come in contact with the stone through this channel, whilst another portion will be absorbed from that portion of the wind which comes in contact with the wet stone.

Fox and Harrison,¹ in discussing the presence of nitrate in a decayed piece of sandstone from Rievaulx Abbey, say: "Unfortunately this decayed material presented other unusual features, such as large proportions of calcium sulphate . . ." and "we were unable to account for sulphate in that part of the country, in spite of a search for its origin."

¹ "Some Aspects of Stone Decay," *J.S.C.I.*, April, 1925, pp. 145T-149T.

If this case is considered from a point of view of atmospheric pollution, the following facts present themselves:

Approximately thirty-seven miles south-west of Rievaulx is the city of Leeds. This city is the seat of quite a large number of factories, and it is in the centre of an important coal and iron district. The atmosphere of Leeds is considered to be a polluted one, and there is very little doubt that during high south-west winds, deleterious substances from this neighbourhood will be carried very rapidly into the Rievaulx district. North-west of Rievaulx, fifteen miles distant, is situated Northallerton, and twenty-six miles in the same direction is Darlington, both of which are manufacturing centres, and in the latter case there are iron and steel and locomotive works, besides breweries and tanneries. Approximately twenty-two miles north of Rievaulx are Middlesbrough and Stockton, and both of these towns possess extensive iron and steel and other chemical works, which will contribute towards the production of an atmosphere detrimental to stone. These facts show quite clearly that within a relatively short distance of Rievaulx polluted atmospheres exist from which deleterious substances may be removed by the stone, especially when it is damp or wet, and it appears highly probable that some, if not all, of the sulphate found in the stone of Rievaulx Abbey is produced in this manner.

At this point it is convenient to consider what part natural joints, cleavage planes, current beddings, etc., play in the process of decay.

The possibility of the presence of minor fissures or joints in stone, which are invisible until such time as pressure or exposure to the weather opens them up, is admitted by experts, and there is every reason to believe that their existence contributes towards the decay of stone, if only to a small extent. Once these fissures open up, then polluted rain-water will gain access to the interior of the stone, and there commence its deleterious action (see pp. 150 and 185). In some stones the risk of disintegration due to water

freezing in the fissures will exist. It should be noted that even granite is liable to contain incipient fissures.

The tendency of rock to split into parallel layers, irrespective of what may have been its original structure, constitutes cleavage. The condition which produces cleavage is brought about by the great pressure to which the rocks of the earth's crust have been exposed during the geological ages, the minute and almost microscopical particles of the rocks arranging themselves with their axes at right angles to the direction of pressure. In many cases the original bedding may be entirely destroyed by the cleavage, and generally the rock will split along cleavage planes which may be at a high angle or even at a right angle to the natural bedding of the rock. Whilst this characteristic is very marked in the case of slate, it occurs from time to time in the limestones, sandstones, and in some of the plutonic rocks. It is possible, if only in a minor degree, that cleavage plays its part in the process of decay, and it is more than likely that many of the apparently unexplainable cases of exfoliation on the surface of stones after exposure to the weather may be due to this cause.

Major bedding planes, current bedding planes, and minor lamination planes play a very important role in the decay of building stones. All the sedimentary rocks occur in stratified beds, and the thickness of these beds varies very much. In some cases the beds exhibit throughout their whole mass bands of various thicknesses, some of which are horizontal, and others at various angles to the horizontal. These major bands are often separated by a thin line of material of a darker colour than the general mass of the stone, and often of a different texture. Each band is very often visibly marked with minor thin lines, known as lamination planes; they may be even as thin as $\frac{1}{40}$ inch. These planes in some cases—viz., in types of micaceous sandstones—are very obvious; the small plates of mica, during deposition, have become arranged in planes parallel to the major bedding planes, and in all cases in which this

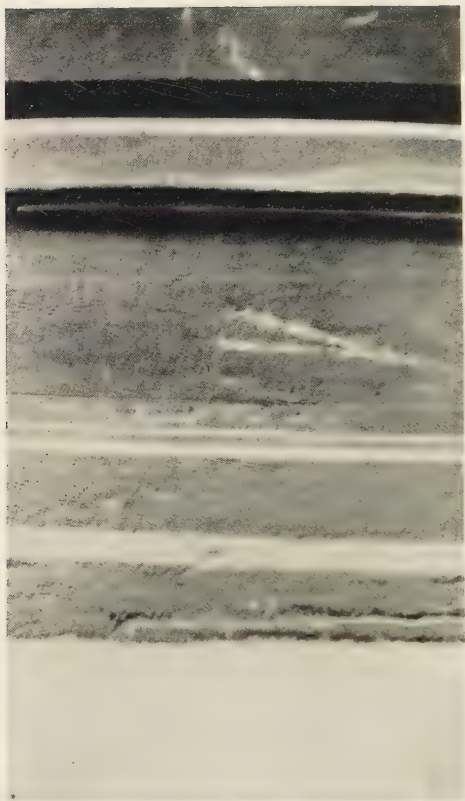


FIG. 43 —WEATHERED HAM HILL STONE,
SHOWING FURROWING ALONG BEDDING
PLANES

To face p. 137

occurs there exists a source of weakness. Often the minor bedding or lamination planes are not accompanied by any visible mineralogical differences, but that these are present makes itself evident when the stone is exposed to the weather by the production of long, thin furrows running as a rule more or less parallel to the bedding planes. It will be seen that we have in these cases an incipient cause of decay which it is difficult to guard against. Whilst dealing with this matter it may be usefully pointed out that the feature known as flow structure, which occurs at times in the igneous rocks such as the granites, is undesirable, and is often a source of weakness if the stones are used in positions which expose them to pressure or crushing strain.

In many rocks, especially in the very homogeneous and compact varieties, and particularly the thick bedded sandstones, both normal and false current bedding may occur, but cannot be easily distinguished. One type or the other nevertheless usually exists, and like the invisible lamination planes, constitutes a source of weakness. In most of the limestones bedding and lamination planes are more or less obvious, sometimes even to inexperienced persons, and in some of the rocks of this type they are very marked sources of weakness, decay occurring in the form of very long, deep furrows. Very fine examples of this type of decay can be seen in weathered Ham Hill stone (see Fig. 43). Not only are bedding and lamination planes a source of "furrowing," but they increase the tendency for the stone to exfoliate, especially when the stone has been fixed in a position at right angles to its natural bed. These facts make it very essential that all stones, whenever possible, should be fixed on their natural bed, and also that this bed should be always indicated on the stone before it leaves the quarry. There is another reason why this should be done, and this is: if the stone is placed on its natural bed it will offer a greater resistance to crushing strain. The writer has observed instances in which the bedding planes of a stone did not become obvious until it had weathered for a number of

years, and then they made themselves evident by decaying in deep furrows at an angle of about 65 degrees from the horizontal, indicating that the stone had been worked in the yard in a manner which allowed it to be fixed in a position in which its natural bed was almost at right angles to the horizontal. Blocks of stone fixed like this will give no end of trouble in some parts of a structure.

It may be difficult for those not acquainted with advanced geology to appreciate the reason why the stone substance along the lines of current bedding should exhibit a condition of weak cohesion, or, on the other hand, a greater tendency to decay than that of the other portions of the stone. If the manner in which sedimentary rocks were laid down is carefully studied, it will be seen that in the various periods of time during which each layer of sedimentary matter was deposited there may have been also a variation in the nature of this material, and in seas which were subjected to periods of quiescence during this process of deposition finer material would be laid down from time to time on the top of that of a somewhat coarser nature; the finer often containing a small proportion of argillaceous or clayey matter. From these remarks it should be readily understood that when these conditions obtained during the formation of sedimentary rocks, the possibility of lines of weakness being set up in the stone at a later period was latent. As illustrative of this may be cited a case in which some new Chilmark stone was fixed in a structure in the year 1923, the face of which, after fixing, looked perfect; but two years later very marked decay was evident in the form of furrows along lines of current bedding, these furrows being on an average $\frac{1}{4}$ inch in depth and $\frac{3}{4}$ inch in width. Careful inspection showed the presence of marl or clayey matter in these beds. Clay is a colloidal substance which, when exposed to water, adsorbs it and forms a structure which possesses a powerful capillary action, and consequently effects the distribution of water throughout its mass in a most thorough manner. When it does this it swells and is no longer able to hold the

particles together, and for this reason, if it is in contact with the clastic which composes a limestone, this will be very easily removed by wetting and driving rain.

Whilst on the subject of current bedding it will not be irrelevant to mention that veins of oxide of iron, produced either by infiltration or by bacterial or chemical action during the quiescent stages of the water above the deposits, very often form weak spots in the building stones.

Some readers will no doubt wonder how it is that some of the sedimentary rocks—for instance, those from which Portland stone is obtained—possess such remarkably good weathering properties. Using this stone as an example, if a number of blocks are carefully examined it will be seen that the bedding planes are not well defined, or in some cases it is impossible to locate them. If a thin section of this stone is examined under the microscope, it will be seen that the material of which the clastic is composed is very closely packed and strongly bound together by a crystalline matrix of calcite, and there also appears to be quite a quantity of shell fragments in the composition of the clastic which are highly crystalline and much harder than the ooliths. When the strata from which Portland stone is obtained was being laid down in the geological ages the process of deposition took place in a great shallow sea which was almost enclosed, and during the deposition this sea was free from mud or clay-bearing currents. The deposits giving rise to the Portland stone beds were composed of coarser to fine shell sands, and the fine deposits were laid down in the still water and contained a considerable amount of the remains of shells composed of aragonite. In those deposits which are coarser and formed in currents the aragonite condition is almost absent, due to decomposition. The granules or ooliths which form a part of the matrix of the rock are due to the coherence of fragments of decayed shells, or due to crystalline chemically deposited calcium carbonate round nuclei which form ooliths with a concentric or a radiate structure. Occasionally there is partial silici-

fication of these ooliths. All this means that the material from which Portland stone is built up is closely compacted, and of a crystalline nature which offers great resistance to atmospheric attack, and it is also a very pure stone—that is to say, free from marly or clayey material.

All rocks, whether compact or not, may contain spots in their mass which differ in their chemical and physical behaviour from the general body of the stone, being weak in their power of resistance to a crushing force and also to the action of those deleterious substances contained in a polluted atmosphere. Another peculiarity associated with both sandstones and limestones is the tendency often shown towards the grains of sand or the ooliths grouping in clusters in which the substance constituting the matrix seems to exert a stronger binding power, a function which may be assisted by the process of secondary outgrowth on the surface of the grains. The clusters are much stronger and more weather-resisting than the other portions of the stone. These two conditions are no doubt among the causes of uneven weathering in the building stones.

The porosity, or, in other words, the percentage of pore space in a stone, varies within wide limits if the igneous rocks are grouped with the sedimentary rocks, but the variation is not quite so great if the sedimentary rocks are considered apart. It should be noted that the term “porosity” is often used when water absorption is meant, and this is an error which must be avoided. As typical examples the following rocks may be considered:

				<i>Porosity.</i>	<i>Water Absorption.</i>
Grey granite	..	..	..	0·12	0·10
Hopton Wood stone	..	..	..	8·36	4·7
York stone	..	..	..	11·94	4·70
Portland stone	..	..	..	12·80	7·20
Doulting stone	..	..	..	14·46	10·87
Red Mansfield stone	..	..	..	14·98	4·58
Monk's Park stone	..	..	..	20·51	7·51
Box Ground stone	..	..	..	22·32	7·75

It will be noticed, on reference to the table above, that a high porosity figure does not mean a correspondingly high water-absorption figure, and as to a certain extent the decay of stone is assisted by the amount of absorbed water retained by it, or, in other words, the slowness of removal by capillary action and evaporation, then a stone possessing a high porosity value will not necessarily decay more rapidly than one with a low value.

Now it is held by some authorities that the destructive action of rain and frost is closely related to the absorptive capacity of a rock, but if this statement is strictly adhered to, then difficulties will arise when attempting to explain how it is that two unlike stones with more or less the same porosity figure behave markedly different when exposed to atmospheric conditions. Whilst the destructive action of rain may be very much assisted by the porosity of the stone, it is questionable whether the same may be said about the action of frost. Water expands one-tenth of its volume on freezing, and before frost can bring about the disintegration of stone it is necessary for its pores to be filled with water to above ten-elevenths of their volume. In a climate like that of Britain it is hardly likely that such a condition will be set up in any of the ordinary building stones. The writer, from his experience and observations, is not able to say that he has come across many cases of disintegration of building stones which can be with certainty attributed to the action of frost; and what cases he has seen are associated with the sandstones.

Dealing with structural defects in buildings which may contribute towards the decay of stone, the following brief notes will no doubt be of assistance to the reader; there is not space in a book of this size to treat of these matters fully.

Settlements.—These usually take place in the early period of the life of a building, and they may cause an opening-up of joints, a cracking of stone in copings, in enrichments, or even in the plain ashlar, a fracturing of damp-proof courses,

a pulling away of flashings, and so on, all of which will allow polluted rain-water and soot, or soil-water, according to the position of the cracks or openings, to gain access to the interior of the stone, with consequent decay of its surface.

Opening-up of Joints.—This defect may occur if bad mortar is used in fixing and pointing, or if the pointing has been skimmed, and afterwards the joints, especially the vertical ones, are subjected to drippings of water from projections above, or destroyed by heavy rains. Open joints allow access to rain and other deleterious substances, which in time will bring about decay of the surface of the stone.

Pressure.—Unequal pressure due to faulty design will set up stresses which are unevenly distributed; in some cases cracks produced by this means will be of considerable length and gape open to the extent of $\frac{1}{8}$ to $\frac{1}{4}$ inch. These cracks will contribute towards the decay of stone in a similar manner to open joints.

Absence of Weatherings or Badly Made Weatherings.—The absence of a weathering will often mean a completely horizontal surface upon which water may remain for a very considerable time, and as this water will always be polluted it has the opportunity of continuing to exert its corrosive action on the stonework whilst present. Badly made weatherings may have depressions on the face of the stone, or they may, in places, slope in the wrong direction, in both cases causing a lodgment of water with the effect just mentioned. Another source of trouble which will be accentuated by these defects is the lodgment of dirt, soot, lichen, moss, and other deleterious matter, which in one way or another attack the stone, this undesirable action being assisted in all cases by the fact that the stone is kept constantly damp. The under-surface of cornices and similar enrichments will also suffer acutely under the circumstances just mentioned.

Badly Made Damp-proof Courses, or the Absence of a Damp-proof Course.—The ultimate result in either of these two cases is the same. A badly made damp-proof course

will allow water to pass through the defective parts and to travel upwards into the plinth of a building, and naturally the absence of a damp-proof course produces a similar action. In both cases this water will carry with it salts extracted from the soil which will act upon the stone at its surface, especially when the water evaporates and crystallization takes place. This is one fruitful source of pitting and scabbing on plinths. It should be noted that splashings off the soil or pavements during rainstorms will also contribute towards this trouble.

Badly Designed or Carelessly Built Roofs.—Sometimes the gutter of a pitched roof is built 3 or 4 feet away from the eave, with the result that rain-water which falls on the portion of the roof below the gutter will run off and drop on the weathering of, say, the main cornice, and if this is not protected by lead sheeting, then the constant dropping of water will eventually bring about trouble. Faulty eave gutterings which may allow water to run over the fascia, along the soffit, and then go on to the stonework, will also assist decay. Defective roof gutterings and flashings, particularly in the case of flat roofs, will eventually cause trouble, and ignoring the damage which may be done to any woodwork on the roof, the water which gets behind the defective flashings and soaks into the stone of the parapet will eventually bring about decay on the exposed face.

Badly Designed or Badly Built Balconies.—Soaking in of water is a cause of trouble in these cases, and it may be brought about by the use of unsatisfactory asphalt or lead covering, the defective construction of flashings, the omission to continue the asphalt or lead covering about 6 inches vertically up the base course of the balcony balustrading, and also up the wall of the building.

Bad Bricks.—There is another very possible source of decay of stone, especially of some types, which does not appear to have been realized by the majority of those connected with the building industry, and that is the employment of badly made bricks in structures which are

relieved by stone facings and dressings. Much can be said about badly made bricks which concerns their weathering properties and so on, but this is a special study in itself; their usual high absorptive properties and the fact that they very often "scum," or an efflorescence of white salts appears on their weather faces, is important to the subject under discussion. The material called "scum" may contain the sulphates, chlorides, or carbonates of magnesium, sodium, potassium, aluminium, or calcium, and as a rule the most abundant of these chemical substances is calcium sulphate. It has been pointed out already that some of these salts, and especially the calcium salt, may be derived from the mortar used in setting, but if in addition to this a further supply can be obtained from the brick, then by the process of capillary action the stone, in the form of dressings and facings, is certain to obtain a share of these salts, which, if the physical properties exhibited by the stone are suitable, will cause decay on its surface by the growth of crystals, as explained elsewhere (see p. 150). Too much care cannot be taken by architects and others to see that the bricks they use are of first-class quality, not only because eventually the facing bricks themselves will decay, but on account of the risk of injuring the stone used in the building. The source of these salts is not a single one. The chief one is the clay itself, but they may be introduced by the use of impure waters in the process of tempering or by the injudicious mixing of ashes or coal slack with the clay, in the one case to relieve the tendency to shrink during burning, and in the other to assist in the operation of burning, or by the action of the kiln gases (which contain some sulphur dioxide) acting upon the calcium salts in the brick earth during firing. The clays themselves contain soluble salts, and in some cases iron pyrites. This latter material on exposure is oxidized ultimately to hydrated ferric oxide, with the production also of sulphuric acid, and this substance will then react with the calcium, magnesium, and aluminium salts, forming sulphates. There are ways and means in the

manufacture of bricks of overcoming a great deal of the trouble of "scumming," but this does not do away with the need for choosing those clays which are as free as possible from pyrites and soluble salts. Weathering and mechanical washing of the clay, and the employment of barium carbonate during the preparation of the clay before burning, relieve the trouble to a very large extent.

Mortars.—Quite a large number of investigators into the causes of decay of building stones have neglected to consider how much is contributed towards this end by the various types of mortar used in building construction. In addition to those employed in masonry, the mortar used in brick-laying will also add its quota to this trouble in those cases in which stone is used as dressings and facings in a brick-work elevation.

Broadly speaking, there are four types of mortar used in the building industry—viz., lime mortar, which is made of well-slaked lime and clean sand in ratios varying between 1 : 2 and 1 : 3; lias lime mortar, which is prepared from slaked lias lime and sand, the ratio of lime to sand varying between 1 : 2 and 1 : 2½; mason's putty, which is a mixture of well-slaked lime and stone dust, usually in the ratio of 1 : 1; and cement mortar, which is made of Portland cement and sand, the ratios varying from 1 : 2 to 1 : 4.¹ There is another mortar used in setting stone and also for pointing which as a rule does not cause staining. Its composition is: white cement, 2 parts; lias lime, 5 parts; stone dust, 7 parts. The source of trouble in regard to all these mortars, so far as the decay of stone is concerned, is the presence of soluble alkaline substances, the chief of which are the soluble calcium and magnesium salts. When quicklime is slaked the calcium oxide (its chief constituent) is converted into calcium hydroxide, a white powder which is somewhat soluble in water; at ordinary temperatures 100 parts of water will dissolve 0.17 part. This substance, whether it

¹ The ratios given are not always used in practice; they may differ according to individual ideas.

be in solution or in the form of a white powder, will gradually combine with the carbon dioxide in the atmosphere and form calcium carbonate.

Now the setting of an ordinary lime mortar depends upon (a) the formation of a colloidal calcium hydroxide; (b) loss of water due to evaporation or absorption by the bricks and the consequent hardening up of the calcium hydroxide gel, which "sets" in a similar manner to, say, gelatin; and (c) the formation of calcium carbonate, which may eventually become crystalline. Whilst the calcium carbonate is far less soluble in water than the hydroxide (100 parts of water will dissolve 0.0018 part at ordinary temperatures), it will react with carbonic acid, forming the bicarbonate, a much more soluble salt, or with the sulphuric acid in the atmosphere, forming calcium sulphate, a more soluble salt still, dissolving to the extent of 0.24 part per 100 of water. The hydroxide is also reacted upon by sulphuric acid forming calcium sulphate.

If sand lime mortar is used for the bedding of building stones, it is practically impossible for the calcium hydroxide contained in the mortar in the centre of the bed, or even that not far removed from the edge of the joints, to become carbonated; careful work done in regard to the testing of modern mortars, and even some of those as old as 2,000 years, has shown that it is only the calcium hydroxide in the superficial layers which becomes completely carbonated. As to how far this change takes place will depend on many circumstances. From the point of view under consideration it is not a matter of great importance whether the mortar sets throughout or not, for, as already indicated, the various lime salts formed are soluble in water, and during the many rainy periods to which the exterior elevations of a building are exposed, some of these salts will dissolve in the rain-water, the solution formed soaking into the stone, and eventually reappearing at the surface, very often along the joints. On evaporation of the water crystallization of the salts takes place in the interstices of the stone in these

positions, creating pressure and thus causing exfoliation and other types of disintegration.

Unfortunately mason's putty is liable to bring about the same trouble, especially when it is composed partly of slaked lime, and from the point of view of constructional masonry the Portland cements are not altogether free from this evil. Sufficient alkaline material can be washed out of these types of cement to cause trouble in some stones, especially at the joints. Careful scientific investigation has shown that free lime does not occur in dry Portland cements, but when water is added for gauging purposes hydrolysis takes place and a certain amount of calcium hydroxide is set free. How it is possible for some of this substance to be washed out of the mortar, and what happens afterwards, has been discussed already. It is important to note that after a number of years a portion of the cement in a mortar will still remain unchanged, and whilst water can gain access the process of hydrolysis will go on slowly with the formation of small quantities of calcium hydroxide. Blue lias lime mixtures are also liable to give up calcium salts to water in a similar manner to that described, and these salts will eventually damage some types of stone.

The addition of gypsum or calcium sulphate to Portland cement or to lias lime, whilst it has its virtues from the point of view of practical working, is certainly detrimental in regard to the damage it may do to stone, especially on account of its comparatively high solubility in water and its very great tendency to crystallize in the interstices of the stone near the surface.

Opinions are very divided as to which are the better types of mortars to use, those containing lime or those containing Portland cement, and until something more suitable is found, the author advocates the use of properly made cement mortars. Whilst he has seen damage done to masonry by the use of lime mortars, he is in a position to state that he has seen similar damage produced by Portland cement mortars, but not to such a large extent.

Possibly what has just been discussed may be more or less disturbing, and will cause some practical men to remark, "What are we going to do if we can't use mortar?" The only answer which can be given at present is: Employ a mortar containing as little soluble calcium salts as possible, and stimulate the various research bodies to seek for a material free of all the defects just named, but at the same time suitable for bedding and pointing masonry and for the laying of bricks.

Non-weather-proof Casements.—These may be a source of trouble owing to water leaking between the jambs, lintel, or cill, and getting into the back of the stone and then coming forward and evaporating on the surface, bringing with it soluble salts which crystallize and produce scabbing and pitting. There are a number of methods of constructing weather-proof casements, but these cannot be dealt with in this book.

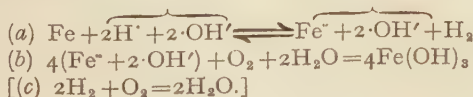
Badly Designed Members in Enrichments.—A good deal of trouble can be caused in the direction of stone decay by constructing enrichments in such a fashion that they cannot be provided with weatherings in order to throw off water. Whilst dealing with this subject the advisability of protecting carved work in the friezes and other parts of stone buildings should not be overlooked; whilst carvings add very greatly to the architectural beauties of a building, they are very liable, if prominently exposed to all weather conditions, to suffer badly, particularly those portions of the carved work which will allow water to lodge on them.

Defective Fall Pipes.—Attention should be given periodically to fall pipes and the water heads attached to these, for if they become choked or fractured they will not only bring about severe decay of the stone, but produce a considerable amount of staining. Even fall pipes kept in a good condition, if they are fixed quite close to the building, will often cause decay owing to the retention of water in the very narrow spaces between the metal and the building face, and they will also, under this condition, bring about staining

of the stone. These latter remarks will also apply to soil pipes. Bath and lavatory waste pipes should not be allowed to discharge into rain-water heads or fall pipes, for if choking takes place, as is often the case under this circumstance, then the soapy and fatty matter which is brought away with the water discharged from these wastes will run on to the stone and will not only cause discoloration, but will materially assist decay.

Iron Cramps and Dowels.—It will not be out of place to mention here the danger of using iron cramps and dowels, or of inserting railing bases or cross-bars into stonework. A careful inspection of many historical buildings and quite a number of comparatively modern structures has shown, in a very marked manner, how much serious damage can be caused by the insertion of iron or steel into stone. The author has had removed in the course of his practical work pieces of stone weighing up to $\frac{1}{4}$ cwt., or even more, which have burst away from the main blocks by the rusting of iron cramps, dowels, or railing bases. A unit volume of iron, when completely changed to rust, will have increased in volume ten times, and when this rusting takes place in a confined space a very considerable pressure will be exerted, and this pressure makes itself evident when it bursts the stone into which the iron has been inserted.

It does not matter whether the dowel or other iron structural member is near the surface or several inches below it; polluted water will reach it eventually and, setting up local electrolysis, produce rust. Even polluted water is not necessary to bring about rusting, for if pure iron is immersed in pure distilled water rusting will occur, owing to its limited solubility and the slight ionization of water. All that is necessary in the final stage is oxygen, which is present in solution in water and in the air. The following equations will explain this:



When metal dowels or cramps are required for masonry joints, then those of copper or a non-rusting alloy such as "Glowray" should be used.

The chief physical or mechanical process involved in the decay of stone will now receive attention in the order indicated on p. 129.

1. **Solution.**—To prepare a solution a solvent is necessary, and water is the most abundant of nature's solvents. It plays, without doubt, a very important part in the decay of building stones, and it may act in the form of:

- (a) Liquid water (rains and mists).
- (b) Solid water (ice).

Liquid water is the chief aggressor, and as in nature it is never pure, but contains substances which can act on the constituents of stone, and as it is the only material (in the broad sense) which comes in contact with stone in a form which can act as a solvent, it makes it difficult to deal with solution in a simple manner. Pure distilled water does dissolve material out of stone, and it will also dissolve the calcium carbonate of limestones, and on this account the decay produced by deleterious substances carried in rain-water will be assisted by the solvent action of the water itself; and in more ways than one, for it will dissolve rapidly or slowly the new compounds formed.

It has been found that there is an alteration in the value of well-defined properties of certain substances when dissolved in what are recognized as inert solvents, and speaking generally, the properties of a substance undergo an alteration when it is dissolved in a liquid. This has created a doubt as to whether the process of solution is a chemical or physical one, and on this account it will be convenient to deal more fully with the subject of solution under the broad heading of chemical processes which cause decay (see pp. 171 to 207).

2. **Pressure caused by Change in Molecular Volume and Growth of Crystals mainly Due to the Formation and Crystallization of New Chemical Compounds.**—The subject of

increase or decrease in molecular volume of substances formed during the decay of building stones does not seem to have received, until just recently, the attention it merits, nor does that of the effect of crystal growth. Molecular volume is understood to be the volume occupied by the molecular weight¹ of a substance, and a change in molecular volume is not a purely additive or subtractive process, but is in part constitutive, or, in other words, it is dependent not only on the number and kind of atoms in the molecule, but also on their spacial arrangement.

The chief substances formed during the chemical decay of building stones are calcium and magnesium sulphates, the former in the case of ordinary limestones, and the latter, with calcium sulphate, in the case of the dolomitic limestones or those sandstones which contain dolomite. The chemical side of the subject will be dealt with in another part of this chapter; here the physical side only is to receive consideration. Calcium sulphate crystallizes in two forms, one of which has the formula CaSO_4 (anhydrite), and the other $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum), and they can both originate from calcium carbonate, the chief constituent of the ordinary limestones. The increase in volume when calcium carbonate (CaCO_3) is changed into anhydrite (CaSO_4) is as 1 : 1.33, and when converted into gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) the increase is considerably greater—viz., as 1 : 2.15. It is very probable that the formation of CaSO_4 takes place first, and this then changes slowly into $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ in the presence of moisture. Taking into consideration dolomite, there is not only the conversion of the calcium carbonate into sulphate, but the magnesium carbonate, MgCO_3 , into magnesium sulphate (Epsom Salts), which is a crystalline substance having the formula $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, and the change in molecular volume in this case is as 1 : 5.3, which is a very considerable one. These increases in molecular volume will create pressure in

¹ This is the weight of the physical unit known as a molecule, and a molecule is the smallest particle of a compound which exists in a free state.

varying amounts, and this will play a part in the process of disintegration of stone in proximity to the surface if the crystals occur there, or along current bedding planes should they form in these positions.

There will be occasion to refer again to the subject of molecular volume in the chapter dealing with the preservation of building stones.

Pressure is also produced by the growth of crystals, and this exhibits itself not only in the case of the increase in size of newly formed crystals of calcium sulphate and magnesium sulphate, but in the crystallization of ammonium sulphate from its solution, which in certain instances gets into stone from the atmosphere. The process of crystal growth is not at present perfectly understood, but careful observations have established the fact that when a crystal forms and grows certain definite forces come into play. Before a substance can crystallize from its solution it is necessary for that solution to be in a condition of saturation. If the process of crystallization be rapid, then the crystals are usually smaller than if the process be slow, and under the conditions usually existing in the building stones the act of crystallization will be slow, resulting in comparatively large crystals which will continue to grow at the expense of any small ones formed at the same time. Now the growth of a crystal may be likened to the work of laying bricks, molecules of the substance which is crystallizing taking the place of the bricks, and as these molecules leave the solution surrounding the growing crystal they arrange themselves in orderly positions according to certain definite laws of molecular physics. When a few molecules become deposited on the face of a crystal, further additions become rapid, and the growth will continue as long as a saturated solution is present and all other conditions are favourable. If the forces exhibited by the continual addition of molecules during crystal growth are strong enough to overcome the opposing forces of neighbouring material, then hair cracks are produced which will become wider at a later period and

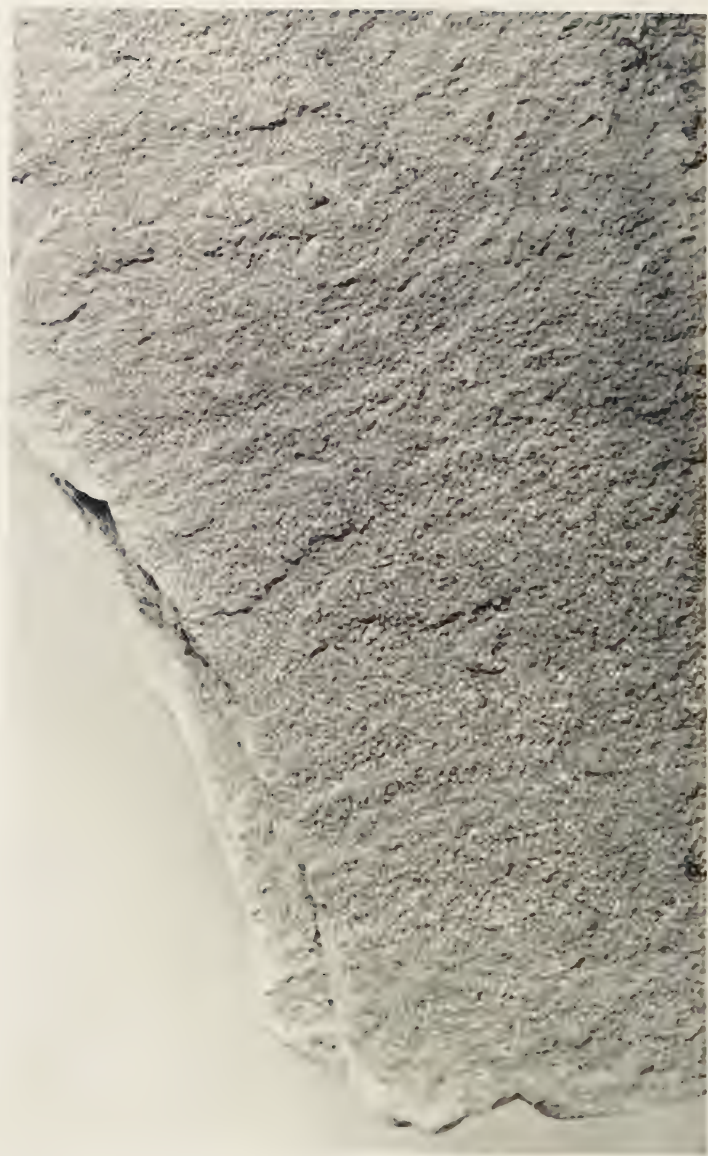


FIG. 44.—A PIECE OF DECAYING RED MANSFIELD STONE, SHOWING CROPS OF CRYSTALS OF
CALCIUM SULPHATE

eventually result in exfoliation or crumbling. The increase in volume due to crystal growth is more or less indefinite, and is governed by surrounding conditions and the supply of the necessary concentrated solution.

Magnesium sulphate and ammonium sulphate are very soluble in water, and therefore are comparatively easily washed out of a stone, but they often remain sufficiently long in position to form crystals large enough to set up strain, with its consequent detrimental effect; 100 parts of water will dissolve 76.9 parts of magnesium sulphate or 71 parts of ammonium sulphate at 0° C. Calcium sulphate is far less soluble (0.24 part of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and 0.179 part of CaSO_4 will dissolve in 100 parts of water at 0° C.), and therefore it is not removed very rapidly, but the crystals continue to grow, and with this growth considerable strain or pressure is set up which ultimately causes a stone to split.

It is not only the limestones which suffer through the formation and crystallization of calcium sulphate, but those sandstones which contain, as part of the natural binding material, calcium carbonate or calcium and magnesium carbonates. The dolomitic limestones or the magnesian limestones and the dolomitic sandstones suffer very badly from this type of decay. The author has very carefully examined decaying pieces of Anston stone, and has found patches of crystals of magnesium sulphate as well as very large quantities of crystals of calcium sulphate, and he has seen the same many times between the laminae of decaying red Mansfield stone. Often, however, crops of crystals of calcium sulphate only are to be seen, the magnesium sulphate being washed out entirely. Fig. 44 shows large numbers of crops of crystals of calcium sulphate on the inner side of a piece of red Mansfield stone which has been split away from a cornice by their growth. At times the crystals of calcium sulphate appear in the tabular form and not in the form of wart-like excrescences, and they produce a glistening appearance on the surface of a decaying stone.

In Figs. 45 and 46 will be seen the formation of decay

which Tadcaster stone undergoes, the stone in the case illustrated becoming converted into calcium and magnesium sulphates, the exfoliation and granulation being produced chiefly by the force exhibited during crystal growth. Fig. 47 illustrates a case of intensive decay of Tadcaster stone produced by grouting in a stop with fat lime mortar; the stop and the grout will be seen in the middle of the illustration.

The author recently came across a case of decay of sandstone in which ammonium sulphate played the chief part. The stone in question was obtained from a quarry near Sheffield, and the natural binding material or matrix was chiefly silica, the subsidiary binders being iron and aluminium oxides. The feature of the decay was that of the surface crumbling into a more or less granular powder composed of particles of mica and large numbers of sand grains. The decay seemed to take place chiefly in proximity to the joints, and it was first of all thought that the trouble was caused by the leaching out of the alkaline earth salts in the mortar and their passage into the stone, where they crystallized, and in doing so created pressure which eventually resulted in disintegration; but on making a chemical examination of some of the decaying stone, it was found that calcium compounds were absent, and that there were only small traces of sodium salts and chlorides; this fact eliminated the "salts" from the mortar theory. What was found, however, was a considerable quantity of ammonium sulphate, with some acid ammonium sulphate, and it was noted that a cold aqueous extract of a piece of the stone reacted distinctly acid to litmus. It is a very well-known fact that sand and also sandstones have the power of strongly adsorbing¹ ammonium sulphate, and it appears in the case now under consideration that the stonework had been constantly in contact with an atmosphere containing moisture and this salt, and that the sulphate

¹ In simple language, the power a surface has of retaining a substance with great tenacity.



FIG. 45.—DECAYING TADCASTER STONE

To face p. 154

had become adsorbed in the form of a solution, and then when the water had evaporated at the surface the ammonium sulphate crystallized out, and in doing so disintegrated the stone. This process was no doubt assisted by the fact that the acid and normal salt when in the ionized state, whilst in solution in water, acted chemically upon the iron and aluminium oxides of the subsidiary binding material sufficiently to weaken their hold upon the sand grains.

Whilst dealing with the subject of salts which crystallize on and just below the surface of a stone, the matter of quarry sap (or quarry water) should receive some attention. The author formed the opinion, some time ago, that in certain cases decay had commenced by the crystallization of salts brought forward by quarry sap after the stone had been fixed, and during the last few years he has been in the position to observe cases which have shown that his opinion was correct. The amount of quarry sap in limestones may vary from about $\frac{3}{4}$ to $5\frac{1}{2}$ per cent.; in the sandstones it occurs in quantities up to 11 or 12 per cent., and in chalks it may be as high as 20 per cent. The salts contained in the quarry sap will naturally vary according to the nature of the stone, and also that of the overlying strata known as overburden. "Overburden" is a somewhat elastic term which is used to cover the soil, subsoil, clay, sand, or gravel, and often all the inferior rock which may lie on the top of the useful stone, and which has to be removed before quarrying can be started. Quarry sap gets into stone whilst it is in the earth; the water which soaks into the soil passes through the subsoil, etc., and into the bed rock, and during this journey takes up soluble salts, which are carried into the stone via joints and fractures, and through the interstices by capillary action. This process will go on until the stone becomes saturated, and in most cases it may have taken centuries to complete this process.

Having become acquainted with a number of cases in which decay has been started by the crystallization of salts from quarry sap, it seems quite a reasonable proposition to advo-

cate the seasoning of all building stones in order that at least some of the quarry sap may evaporate and deposit on the surface its dissolved mineral matter, which would then be removed during the working of the stone and before it is finally fixed in the building. There is no doubt whatever that a very useful purpose would be served by submitting to analysis the quarry sap from different stones.

Another source of "salts" is the soil, and in many cases in which soil has become piled up against the plinth of a stone building crops of crystals will be found thereon, often associated with a certain amount of exfoliation, between the laminæ of which crystals will be present also in many instances. A qualitative analysis of a specimen of "salts" occurring in this manner on Portland stone showed it to contain a large quantity of sodium sulphate, a small quantity of calcium sulphate, and a trace of sodium chloride. A portion of these "salts" was found to consist of stone dust, and as they were removed from the face of the stone without the use of any force but that of brushing gently with a soft brush, evidence is secured that during the growth of the crystals comprising these "salts," sufficient pressure was set up to loosen portions of the surface of the stone.

The presence of calcium, magnesium, and ammonium sulphates in various types of stone undergoing decay has been proved by several workers, and the following tables dealing with this matter will no doubt be of interest to the reader.

TABLE IV.—ANALYSIS OF CRYSTALLINE INCRUSTATION FOUND IMMEDIATELY BEHIND A LARGE FLAKE THAT BECAME DETACHED FROM ANSTON STONE IN A LONDON BUILDING.¹

<i>Calcium sulphate</i>	..	..	..	10.00 per cent.
<i>Magnesium sulphate</i>	..	..	..	37.70 " "
<i>Ammonium sulphate</i>	..	..	..	2.40 " "
Stone dust	..	..	..	44.50 " "
Moisture	..	..	..	5.60 " "

¹ Due to Fox and Harrison; see *J.S.C.I.*, April 3, 1925, p. 146T.

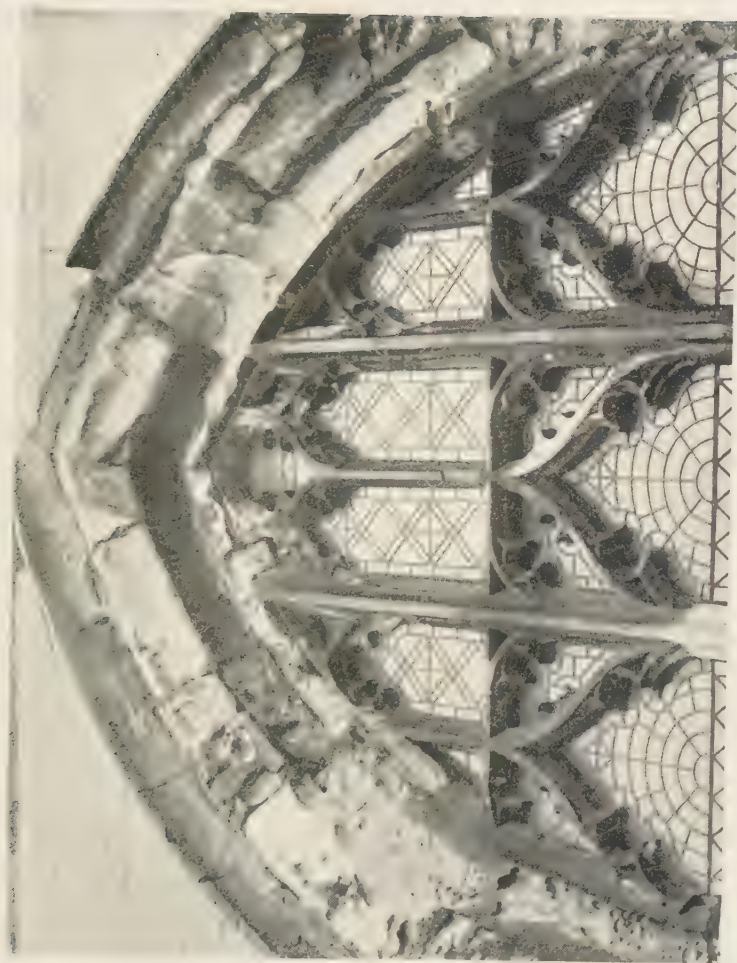


FIG. 46.—DECAYING TADCASTER STONE

TABLE V.—STONE FROM LINCOLN CATHEDRAL : AN
OOLITIC LIMESTONE.¹
Interior.

<i>Boring.</i>	$0\frac{1}{4}$ Inch (per Cent.).	$\frac{1}{4}\frac{1}{2}$ Inch (per Cent.).	$\frac{1}{2}\frac{3}{4}$ Inch (per Cent.).	$\frac{3}{4}$ -1 Inch (per Cent.).
Water	1.30	1.30	1.50	1.10
Insoluble in hydrochloric acid	2.90	2.70	3.00	2.80
Iron and aluminium oxides	7.30	8.60	4.90	5.40
Calcium carbonate	79.92	79.23	85.96	86.91
<i>Calcium sulphate</i>	4.32	4.08	3.72	2.44
Carbon dioxide in excess ..	4.24	4.04	0.68	1.16

Exterior.

Water	0.90	0.80	0.60	0.90
Insoluble in hydrochloric acid	4.00	2.80	3.00	2.80
Iron and aluminium oxides	1.70	2.60	2.70	2.60
Calcium carbonate	87.73	90.37	91.21	91.44
<i>Calcium sulphate</i>	2.68	0.98	0.51	0.46
Carbon dioxide in excess ..	2.60	2.04	1.57	1.57

The maximum amount of calcium sulphate found in the various beds in the quarry from which this stone was obtained is 0.17 per cent. Professor Laurie points out that the percentage of calcium sulphate is about one-half that found in the stone from the inside of the cathedral, and he thinks that the probable explanation of this is the washing of the external stone by rain, and the consequent solution and washing away of the calcium sulphate. With the object of supporting this explanation, Laurie made an experiment on a piece of decayed calcareous stone obtained from a building in the neighbourhood of London. This stone was washed with water from a watering-can on four successive days, and a portion of the stone examined before and after the process, with the results given on p. 158. The author has appended a further set of figures which he has calculated from Laurie's in order to make the comparison between before and after clearer to the unscientific reader.

¹ Prof. Laurie, *J.S.C.I.*, February 27, 1925, pp. 88-89t.

PROFESSOR LAURIE'S FIGURES.

	<i>Before</i> (per Cent.).	<i>After</i> (per Cent.).
Water	9·9	12·5
Organic matter	4·4	4·5
Silica	53·6	58·9
Iron and aluminium oxides ..	2·5	2·8
Calcium oxide	9·6	7·8
Carbon dioxide	1·1	1·0
Sulphur trioxide	18·8	12·2

AUTHOR'S FIGURES CALCULATED ON PROFESSOR LAURIE'S.

	<i>Before</i> (per Cent.).	<i>After</i> ¹ (per Cent.).
Water	9·9	9·9
Organic matter	4·4	4·6
Silica	53·6	60·5
Iron and aluminium oxides ..	2·5	2·9
Calcium carbonate	2·5	2·5
<i>Calcium sulphate</i>	19·9	16·3
<i>Excess sulphur trioxide</i> ..	7·1	3·0

In decaying red Mansfield stone taken out of two buildings in London, the author has found calcium sulphate, magnesium sulphate, ammonium sulphate, and ammonium chloride.

3. **Attrition, whilst the Stone is Dry or Wet, produced by Wind, Wind-blown Grit, Hail, and Heavy Rains.**—The destruction of the surface of stone by attrition, although to a certain extent localized, is a great deal more common than is generally supposed. All classes of stone are subject to the abrasive effects of wind-blown grit, whether they be in a dry or wet condition, and in the case of those stones which absorb appreciable quantities of water, their much softer condition when wet materially assists the abrasive agent in removing the immediate surface. In inland cities and towns the grit will originate chiefly from macadamized roads, whilst in many coastal towns it will also arise, and chiefly locally, from the sandy seashore. High winds will not only carry gritty and dusty material considerable distances, but

¹ Calculated on basis of 9·9 per cent. contained water.



FIG. 47.—INTENSIVE DECAY OF TADCASTER STONE PRODUCED
BY FAT LIME MORTAR

To face p. 158

to fair heights, and they will bring this material into violent contact with the surface of the stone, thus in time loosening the particles, and finally removing them. Naturally the lower portions of stone structures, such as plinths, will suffer the most severely from this type of decay.

High winds alone, also heavy rains and hail, act, generally, as secondary agents, the force of impact or a sweeping action removing any loose matrix or clastic which has got into this condition owing to a chemical reaction between, say, the deleterious substances in the atmosphere and the calcium carbonate of the limestones.

The furrowing along current bedding planes, the erosion of arrises, and the destruction of enrichments, especially those in high relief, are often assisted by one or more of the agents just mentioned.

Figs. 48 and 49 show the effect of attrition produced by the wind and small particles of decaying stone. The weak spots in this stone are gradually eroded away by the wind whirling the particles of stone round and round inside the cavities.

4. Expansion and Contraction produced by Diurnal Variations in Temperature.—The effect of varying temperatures on building stones has received very little attention in this country, and it is a subject which warrants careful investigation because certain evidence which is presented in practice seems to indicate that trouble with decay is, in quite a number of instances, originated by this physical phenomenon.

In Britain the range in temperature variation is not very great, nevertheless the results of temperature changes can be seen on careful inspection. Perhaps one of the chief troubles produced by the expansion and contraction of blocks of stone which compose the different courses in a structure is the cracking and at times the crumbling of the mortar of the joints, with the result that polluted water finds its way into these cracks. In this connection cracks produced by a shrinking of the mortar or pointing when

this has been badly made must not be confused with those just mentioned.

How great the expansion and contraction is will depend upon the maximum and minimum temperatures to which the stone is exposed, and how much fracturing of the matrix or clastic which takes place will depend upon the powers of resistance to strain possessed by the parts affected. Strain is produced in any case, and there is very little doubt but that continual alternate expansions and contractions will result in local fracturings to a more or less marked degree after a period of time. The weak spots thus produced will act as decay centres in regard to other physical agencies in addition to those of a chemical nature.

No doubt it will be very clear to all those acquainted with the structure of stone that a mass of it is, speaking strictly, not homogeneous, and that the coefficient of expansion of the constituent particles will vary to a lesser or greater extent according to their nature. As the temperature of a piece of stone is raised every particle will expand more or less, an action which will cause crowding with resistless force each against its neighbour, and at the same time the natural cement will be subjected to strain. There will be also a tendency for fracture to take place along cleavage planes where definite crystals are present. Irrespective of heterogeneity, the degree of expansion and contraction in a piece of stone must be uneven on account of the differences in temperature between the immediate surface and that a few inches below it; this point has been considered in connection with the warping of marbles (see p. 111). It is most likely that hair cracks are produced eventually by temperature changes, and when these are once formed, ingress for polluted water is the result, with consequent local decay.

Very few figures have been published on the expansion of building stones, and from the table given on the following page it will be seen that these vary to a somewhat marked degree.



FIG. 48.—DECAYING TADCASTER STONE

Showing “pot holes” produced chiefly by attrition due to wind and small particles of decaying stone

To face p. 160

TABLE VI.

Granites :

0.000004825	inch for 1° F.	(Totten).
0.000004380	„ „ „	(Adie).
0.000008680	„ „ „	(Bartlett).

Sandstones :

0.000009532	inch for 1° F.	(Totten).
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White Marble :

0.000005668	inch for 1° F.	(Totten).
0.000006130	„ „ „	(Adie).

In order to give the reader some idea of the variation in expansion of some of the minerals of which stones are composed, the following table is given:

 TABLE VII.—MEAN COEFFICIENT OF CUBICAL EXPANSION.¹

<i>Calcite</i>	..	..	..	..	0.00002
<i>Hornblende</i>	..	..	..	..	0.0000204
<i>Tourmaline</i>	..	..	..	..	0.000022
<i>Dolomite</i>	..	..	..	..	0.000035
<i>Orthoclase</i>	..	..	..	..	0.00017
<i>Quartz</i>	..	..	..	..	0.00036

It has been discovered that when stone has been caused to expand it does not contract to the same amount; it has a permanent “set.” The following are a few results obtained by the Ordnance Department of the U.S.A.,² which will no doubt prove instructive to the reader. Bars of stone were prepared 20 inches long, and they were heated from 32° to 212° F. and then cooled again to 32° F. The mean deformity of several types of stones are given under:

<i>Granites</i>	..	..	..	..	0.009 inch.
<i>Marbles</i>	..	..	..	..	0.009 „
<i>Limestones and dolomites</i>	..	..	..	..	0.007 „
<i>Sandstones</i>	..	..	..	..	0.0047 „

¹ “Stones for Building and Decoration,” p. 419.

² “Report on Tests of Metal, etc., at Watertown Arsenal: U.S. War Department, 1895,” pp. 322, 323.

A further fact which should not be lost sight of is that when a crystal is subjected to heat expansion is irregular, that along one axis being different from that along another, and in a stone which contains definite crystals this matter of minor variations in amount of expansion may add its quota to the effect produced by the whole of the processes of expansion and contraction to which stone is subjected under suitable conditions. As an example, the coefficients for a crystal of calcite in two axial directions are 0.000026315 and 0.0000054 respectively, making a difference of 0.000020915, which from a comparative point of view is considerable.

The amount of lineal expansion for stone may appear small when expressed in terms of unit of length (see Table VI.), but when considered in regard to a coping in sandstone, say, 5 feet in length, it is comparatively large and quite sufficient to cause trouble eventually. A few examples will make this clear. For a temperature rise of 25° F., the lineal expansion of this piece of stone will be 0.01429 inch; for a rise of 35° F., 0.02001 inch; for a rise of 50° F., 0.02859 inch; and for a rise of 96° F., 0.0549 inch.

The effect of temperature changes are more obvious in those countries the climate of which is hotter than that of Britain and subjected to greater variation. Many very marked examples of decay produced by expansion and contraction are to be seen in the cities and towns of America and India.

5. Pressure Produced by the Expansion of Water due to Freezing.—Whilst the freezing of water in the interstices of rocks in their natural positions is undoubtedly the cause of a certain amount of disintegration, the effect of frost due to its freezing the water contained in building stones when in their positions in structures is not anything like so serious a matter. It seems, from many practical examinations of building stones *in situ*, the making of microscopical examinations, and a study of the literature on the subject, that too much stress has been laid on this probable source of decay,



FIG. 49.—DECAYING TADCASTER STONE
Showing "pot holes" produced chiefly by attrition due to wind and small particles
of decaying stone

To face p. 162

and the statements made in some textbooks regarding this subject are inferential only, the inference having been drawn from the fact that the surfaces of rocks whilst in the earth are frequently broken up by frost. Careful consideration will make it clear that the conditions are quite different. Whilst in the earth it is possible for a rock to become waterlogged and the pores filled, or almost entirely filled, with water, but in the cases of stones in a building, to reach this condition is, with very few exceptions, a practical impossibility. When fixed in a building, stone is exposed in the majority of instances on one face only, and during a rainstorm the water which soaks into the stone will travel (in the case of the greater number of most frequently used building stones) towards the dry portions in the interior, and under these conditions it never rains sufficiently long in this country to bring about the waterlogging of stone.

It has been found in masonry practice that whilst the limestones are, speaking generally, free from trouble due to frost (disruption does occur at times), certain types of sandstones are liable to suffer in this direction, especially if fixed whilst green and containing quarry sap, or if saturated with water at the yard and then fixed in this condition, or if the position in the structure allows water to remain on the surface for a considerable time. Some of the sandstones which suffer from the attack of frost are certain of the York stones, Pennant stone, and Blue Forest-of-Dean stone.

For convenience in studying capillary action in relation to building stones, the pores of the stones are considered as a collection of capillary tubes, but as this conception is apt to mislead the average reader, a description of what is seen when the surfaces of certain of the building stones are examined microscopically is given below. For the demonstration six typical types of stones were examined, the magnification in each case being 72 diameters. The stones chosen were Portland, Ancaster, and Park Nook of the

limestone series, and Blue Forest-of-Dean, Bristol Pennant (Blue), and a South Devonshire Millstone Grit in the sandstone series.

Portland Stone.—A prepared and smooth surface of this stone showed large and small cavities irregular in shape, a number of which appeared to run into each other. Many of the cavities looked like small druses, being lined with tiny crystals of calcite. Some contained one or two large crystals of this mineral, and others were almost filled with it. The surface had a somewhat scurf-like appearance, and the clastic was set in a very fine crystalline matrix of calcite.

Ancaster Stone.—A smooth face showed very few cavities, and all of these were small and lined with crystals. The surface was covered with a scurfy layer, which in places was lifted as if a tiny eruption had taken place underneath; the whole of this scurfy layer was somewhat sugary in appearance and full of tiny pores. Some of the cavities on the surface were partly covered with a "roof" of this scurf-like calcite.

Park Nook Stone.—A prepared surface of this stone showed a very large number of "pits" which appeared to be produced by the removal of ooliths, and particles of fossil polyzoa, which constitute the clastic. The clastic was seen to be set in a solid mass of crystalline dolomite which possessed a sugary appearance. The only so-called pores to be seen in this stone were those cavities or "pits" produced during the preparation of the surface.

Blue Forest-of-Dean, Blue Bristol Pennant, and South Devonshire Millstone Grit.—A prepared face on these stones, when examined with a microscope, showed a large number of very tiny cavities, and a smaller quantity of comparatively large ones, and in each case the surface appeared scurfy. Speaking generally, the cavities were connected together.

It appears that the normal function of absorption of water by stone is not governed by the percentage of pores, but rather by the surface available throughout the mass,

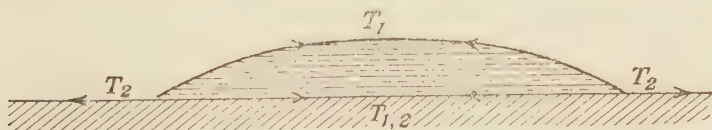
which when wetted by water can exhibit interfacial tension¹ of the type which produces readily a spreading of the liquid; this function will include what is known as capillary attraction, or, to use the more correct expression, capillary action. To obtain capillary action, capillary tubes are not necessary; two surfaces, if separated by a very short distance, will produce this phenomenon in the presence of a liquid. The flow produced in a stone seems to depend on interfacial tension, and if this is of the correct type it will always tend to reduce the amount of water held in the interstices in proximity to the surface which is being wetted.

With the object of seeing how far water will penetrate into stone, two sets of experiments were made: in the one three limestones were used, and in the other three limestones and three sandstones; and in order to obtain a permanent record of the extent of penetration the water was stained by a dye called Cyananthrol R.B., as it was found that only a portion of this dye was removed from the water (by the

¹ As a matter of fact, interfacial tension is the main determining factor in wetting.

A simple explanation of interfacial tension is not forthcoming, and the diagram below will no doubt assist those who are not acquainted with the branch of physics dealing with this subject to understand what is meant.

The directions exerted by the various forces are indicated by arrows. T_1 is the surface tension of the water; T_2 the surface tension



of the solid (stone); $T_{1,2}$ the interfacial tension of the liquid to the solid.

If the force T_2 is greater than the combined forces of T_1 and $T_{1,2}$, *interfacial tension is low*; then the drop will tend to form a continuous film and flow will be assisted [$T_2 > T_1 + T_{1,2}$]. If, however, the force T_2 is less than the combined forces of T_1 and $T_{1,2}$, *interfacial tension is high*, the drop will tend to roll up, and spreading will be retarded [$T_2 < T_1 + T_{1,2}$].

phenomenon known as "capillary analysis") when the solution was placed on the stone, and the balance which remained in solution was able to colour the stone as far as the water penetrated.

In the first set of experiments the same number of drops were placed on each specimen of stone, and in the same central position, two drops at a time, allowing each application to soak in before applying a further one. As the solution was soaking into the stone microscopical observations were made, and it was seen, where surface cavities were present, these remained full for a short time after the solution had soaked into the other portions of the stone, but they emptied gradually by the same process of soaking in. Twelve drops were used in each case, after which the stones were allowed to remain overnight, and the next morning the stains were measured across their diameters, and then the stones were broken across the centre of the stain and the depths of penetration were measured also. The following are the results:

			<i>Park Nook</i> (cm.).	<i>Ancaster</i> (cm.).	<i>Portland</i> (cm.).
Diameter of stain	..	..	2.0	2.1	2.9
Ratio	..	..	1.0	1.05	1.45
Depth to which water had soaked			1.1	1.3	1.4
Ratio	..	..	1.0	1.18	1.27

These observations show that the stone possessing the greatest number of large cavities, as seen by microscopical examination, allows water to spread to a far greater extent and to sink in deeper than the stone which possesses very few or not any large cavities.

In the second series of experiments six typical specimens of stone were used, three limestones and three sandstones: Portland, Ancaster, Park Nook, Blue Bristol Pennant, Blue Forest-of-Dean, and South Devon Millstone Grit respectively. In this series three drops of stained water were placed on each stone, allowing the first drop to soak in before adding the second, and so on, each drop being placed over the centre of the first one. All the stones were

allowed to remain overnight, and the next morning measurements were made of the diameters of the stains and the depths of penetration. In regard to the limestones, whilst water was soaking in, the behaviour was the same as in the first experiments, but in the case of the sandstones the following points were noted: On each of the three sandstones the drop of water flattened out almost immediately, and an irregular ring formed round it which remained very wet during the whole period occupied in soaking into the stone. For a time the water appeared to hang about the surface of each stone, behaving in a similar manner to that when placed on a glass surface which had been greased by rubbing with oleine. It should be noted that it is not possible to obtain exactly the same results in a series of tests on the same block of stone if different areas are wetted, owing to slight differences in the texture, and the figures given are the averages of those obtained from three sets of experiments. It is also as well to bear in mind that, as a rule, water will soak into a stone much quicker if applied to a face at right angles to its natural bed. The figures obtained in the second series of experiments are set out in Tables VIII. and IX.

TABLE VIII.

	<i>Park Nook.</i>	<i>Ancas- ter.</i>	<i>Port- land.</i>	<i>South Devon Mill- stone Grit.</i>	<i>Blue Bristol Pen- nant.</i>	<i>Blue Forest of Dean.</i>
Diameter of stain } on surface	1.8 cm.	1.9 cm.	2.2 cm.	2.5 cm.	2.5 cm.	2.5 cm.
Depth to which } water had pene- trated	1.40 cm.	1.50 cm.	1.90 cm.	0.50 cm.	0.45 cm.	0.50 cm.
Time one drop } took to soak in	2 min.	2 min.	7 min.	53 min. ¹	58 min. ¹	60 min. ¹

¹ These figures may appear high, but when compared with the time a similar sized drop of water (same volume) took to evaporate off a glass plate (3 hours 50 minutes), it will be clearly seen that, whilst a little may be lost by the process of evaporation, the greater quantity will have soaked into the stone.

TABLE IX.—RATIOS.

	<i>Park Nook.</i>	<i>An- caster.</i>	<i>Port- land.</i>	<i>Blue Forest of Dean.</i>	<i>Blue Bristol Pen- nant.</i>	<i>South Devon Mill- stone Grit.</i>
Spreading ..	1.0	1.22	1.22	1.39	1.39	1.39
Penetration ..	3.11	3.33	4.22	1.11	1.0	1.11
Length of time taken by one drop to soak in	1.0	1.0	3.5	30.0	29.0	26.5

A careful examination of Tables VIII. and IX., with the following explanations, will, it is hoped, help the reader to understand why some of the sandstones, such as those of a similar nature to the types used in the experiments, are very liable to suffer damage from frost, whilst the limestones are very much more free from this danger.

It will be noted, on comparing the limestones with the sandstones, that there is not so very much difference in the area wetted by the spreading of the drops of water, but in regard to the depth to which the water penetrated it is very much greater in the case of the limestones than the sandstones. Now, as the same volume of liquid was used for each stone, then there must have been considerable concentration in the tiny cavities at the immediate surfaces of the sandstones. As already explained (see p. 141), water expands approximately one-tenth of its volume on freezing, and for the action of freezing to make itself felt in a stone the pores or cavities must be filled with water to above ten-elevenths of their volume. That the tiny cavities in proximity to the surface of some of the sandstones do become filled or almost filled with water when wetted by this substance seems to be indicated by the result of the experiments just described, and the behaviour of these stones in the field.

The cause of the differences in the rapidity and depth of

penetration of water exhibited by the limestones and sandstones seems to be associated with interfacial tension phenomena; variations in the natural arrangement of the minerals constituting the matrix and clastic, and differences in their physical properties, are of importance in this case.

Further, to what has been written in regard to the possibility or not of the freezing of water causing damage to stone, the two following points should be considered:

- (a) Water enclosed in the pores of a stone may not freeze until a temperature lower than the normal freezing-point is reached.
- (b) When stone becomes very cold any water contained in it will come to the surface by capillary action, and hence freeze there if the temperature falls low enough.

As soon as time permits, the author intends to give further attention to this subject, as it appears to him of great importance from many points of view.

6. Mechanical Action (Pressure) Produced by Growing Roots or Hyphæ of Plants.—A certain amount of disintegration or decay of stone is due to this kind of mechanical action, and both the lower and higher orders of plant life can contribute towards it. Pressure is set up by the growing parts of plants by turgescence (turgor). Turgor is brought about by the internal pressure in plant cells stretching the cell walls, and it should be noted that this pressure may reach at least $3\frac{1}{2}$ atmospheres, and in some cases 5 to 10 atmospheres.

Careful examination has shown that roots and root hairs which have insinuated themselves into cracks in the stone often completely fill these cavities. It was discovered by Pfeffer that an external pressure on growing plant cells will, after a time, frequently bring about an increase of turgor, and consequently the counter-resistance to the external pressure is intensified. In many cases the external resistance is sufficiently great to resist that produced by turgor, but

when the stone is partly decayed and wet, then portions of it will break away.

The hyphæ of the fungus portion of lichens can produce mechanical disintegration of, say, limestones by exerting pressure due to turgor and thus fracturing the calcite matrix and setting free the fine clastic, such as ooliths, which will then be blown away by wind or washed away by rain when an opportunity offers itself. Cracks can be produced in some open-grained stones, or, if present, increased in size by growing roots exerting a pressure due to turgor. Should cracks exist, say in old and much-weathered stone, and these cracks become preliminarily charged with soil by wind carriage, then later grasses or small plants will take root, and the growing tap-root and the root hairs may, and often do, exert sufficient pressure to increase the size of the openings and bring about a more rapid decay of the stone.

All this is mechanical action; the chemical reactions due to plant growth are dealt with on p. 171.

Whether the surface of stone is weakened, from the point of view of resistance to weather conditions, by machine working or hand working in the yard, or when it is sculptured, is a controversial subject. After examining a number of sections of different stones by the aid of the microscope, it will not require much stretching of the imagination to understand how easily the delicate calcite crystals, or the silica films which form the matrix, can be fractured and caused to leave the finer particles of clastic in a somewhat loosened condition if the stone is subjected to unduly heavy blows or excessive tearing strain. It will be recognized also that there is a possible chance of occasionally producing minute hair cracks in the stone along cleavage planes, which may eventually open up and form means of ingress for polluted water, and result, sooner or later, in local decay.

It has been argued that hand-worked stone weathers better than that which has been machine worked, and *vice versa*. If many historical buildings are carefully examined it will be seen that tool marks are still visible on some of the

blocks of stone, and this seems rather to favour the hand working of stone; yet there are many instances in more or less modern buildings in which hand-worked stone has decayed very rapidly on the surface. The author is of the opinion that careful machine working will not injure the stone, and that the same may be said of hand working, provided the blows are not unduly violent and are directed, as much as possible, at an angle to the surface and not against it. It must be borne in mind that some sandstones (*e.g.* the grits) are difficult to machine work without "bruising" the surface, owing to the very rapid blunting of the tools. With the limestones, like Portland stone, the various Bath stones, Ancaster stone, and so on, the machine tool keeps a cutting edge for a considerable time, and the working is not so harmful to the stone, at least far less so than in the case of hand working.

In these days when speeding-up has become a necessity, machine working as far as possible follows as a corollary, and it should be done with due care and consideration, as should all hand work.

The chief chemical processes involved in the decay of building stones are now to be considered.

(a) **Action of Acids, including certain Plant Acids.**—Stone is liable to attack from certain acids which are carried in the atmosphere, especially in the neighbourhood of manufacturing centres, and among these can be mentioned sulphuric, hydrochloric, nitric, and carbonic acids. With reference to the first three, they do not as a rule exist in the atmosphere in any large quantity in the free state, but usually in combination with bases in the form of sulphates, chlorides, and nitrates, and they are held in suspension in a finely divided state. Eighty or one hundred years ago the occurrence of any great quantity of these substances in the atmosphere was exceptional, but it is not so to-day, for they exist in the atmospheres of all towns and cities, and especially those which are near to or which include certain chemical factories; and this in spite of the

care which has to be taken to conform to the Alkali Act.

Carbonic Acid (H_2CO_3).—Speaking strictly, this acid hardly ever exists in the atmosphere as such, but its anhydride, carbon dioxide (CO_2), occurs in varying quantities according to situation; for instance, the average amount found in country atmospheres is 0.006 part per 100, and in the atmosphere of towns it may vary between 0.025 to 0.045 part per 100. There is little doubt that in some of the large cities in which a considerable volume of motor traffic exists the amount of carbon dioxide is greater than the highest figure just given. Carbon dioxide is a product of the complete combustion of either solid, liquid, or gaseous fuels, and it will therefore be quite clear to the reader that in a city which happens to be a manufacturing centre, and in which there is a very considerable volume of motor traffic, the amount of carbon dioxide in the atmosphere (produced by the burning of coal or gas in domestic fires and boiler furnaces of factories, and the combustion of petrol used as fuel for motor vehicles) is certain to be larger than that of a country village or town; and it is in the large cities that the most stone is found in its various buildings.

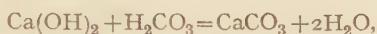
Carbon dioxide is soluble in water (at normal pressure 100 c.c. of water at 0°C . will dissolve 1.796 c.c. of this gas, and at 15°C . 100 c.c. of water will dissolve 1.019 c.c.), and this solution reacts acid to blue litmus paper, turning it red. Undoubtedly when this gas dissolves in water it forms carbonic acid, but it should be noted, however, that this acid is unstable, and has not been isolated, and it decomposes at ordinary temperatures when its solution is exposed to the air, with the escape of carbon dioxide. It is highly probable that the reaction is reversible, as indicated by the following equation:



and the system is in equilibrium when but a small portion of the dissolved gas has produced carbonic acid. Now, if

a base be present it will react with the carbonic acid and form a carbonate; then more water and carbon dioxide will combine, forming a fresh quantity of carbonic acid, and this will react with a further quantity of base, and so these reactions will continue until all the carbon dioxide has become exhausted.

If a base such as calcium hydroxide be present—and this is the case in the mortars—then calcium carbonate is formed; but in regard to



the limestones and dolomites, the two substances upon which carbonic acid can react are not free bases, but are already normal salts of this acid—viz., calcium carbonate and magnesium carbonate. These substances are slightly soluble in water—for instance, calcium carbonate at 15° C. is soluble to the extent of 0.0018 gramme in 100 c.c. of water, whilst in the case of magnesium carbonate at the same temperature 100 c.c. of water dissolves 0.0106 gramme.

It should be noted that calcium carbonate imparts an alkaline reaction to water if it is kept in contact with it, and this is, in all probability, owing to slight hydrolysis, thus:



When this takes place calcium bicarbonate and the base, calcium hydroxide, are produced, both of them being more reactive with strong acids than the normal calcium carbonate, and the latter being responsible for the alkaline reaction.

When water in which carbon dioxide is dissolved (a weak solution of carbonic acid) comes in contact with calcium carbonate in solution, the following reaction takes place:



Now the bicarbonate or acid carbonate which is formed is more soluble in water than the normal carbonate—for instance, 100 grammes of water saturated with carbon dioxide will dissolve, at 0° C., 0.07 gramme calcium carbonate, which is equivalent to 0.113 gramme calcium bicarbonate. A very simple method of proving that calcium carbonate

can be dissolved in carbonic acid is to prepare a thin suspension of this substance in water and pass carbon dioxide into it until the suspension becomes quite clear. Calcium bicarbonate is not a very stable substance, and it cannot be isolated by concentrating its aqueous solution. This solution decomposes slowly when exposed to the air, with the escape of carbon dioxide and the precipitation of normal calcium carbonate.

It will be seen from these remarks that if water containing carbonic acid comes in contact with the calcium carbonate of limestones the bicarbonate is formed which goes into solution, and part of this solution is washed away from the surface of the stone.¹

This process of bringing about decay, acting alone, is a slow one, but it is undoubtedly the chief one in those country districts in which the atmosphere is considered pure. In atmospheres which suffer from periods of pollution it is of material assistance, as the bicarbonate or the newly precipitated normal carbonate are more reactive with, say, the sulphur acids which come in contact with a stone during these periods.

Dealing with the magnesium carbonate of the dolomites, the matter is somewhat involved. In actual dolomite the magnesium carbonate is in combination with calcium carbonate ($\text{MgCO}_3 \cdot \text{CaCO}_3$), and this substance has a definite crystalline form, refractive index, etc., and it is more difficultly soluble in acids than the normal carbonates of magnesium and calcium. Decomposition of dolomite does, however, take place in the dolomitic building stones, but it is more likely that its origin is due to the presence of sulphur acids in the atmosphere than that of carbonic acid. However, in many of the building stones magnesium carbonate occurs as such, and in these cases carbonic acid can make itself felt to a comparatively marked degree. The solubility

¹ The formation of stalactites and stalagmites and also travertine is due to water highly charged with calcium bicarbonate slowly evaporating with the consequent decomposition of the bicarbonate and deposition of calcium carbonate.

of magnesium carbonate in a saturated water solution of carbon dioxide is much greater than that of calcium carbonate, being 2·21 grammes in 100 parts of carbonic acid solution; this means that more magnesium carbonate than calcium carbonate can be removed from a stone by rain-water contaminated with carbonic acid.

It was discovered by Müller that water containing carbonic acid could act upon other minerals than magnesium carbonate and calcium carbonate, and among these may be mentioned oligoclase, hornblende, magnetite, and serpentine, all of which will be found in one or other of the types of building stones removed from those of the limestones. The amount dissolved is far less than that removed from calcium and magnesium carbonates under the same conditions.

All these reactions may be very slight in degree, but nevertheless they make themselves felt in the course of time.

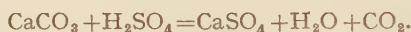
Sulphuric Acid (H_2SO_4).—Compared with carbonic acid this acid is a very strong one, and so far as atmospheric pollution is concerned, it is formed by the complete oxidation of sulphur dioxide. Under the influence of ultra-violet light (light waves of very high frequency, invisible to the naked eye), sulphur dioxide (SO_2) is oxidized to sulphur trioxide (SO_3), which finally unites with the water carried in the atmosphere forming sulphuric acid.

Sulphur dioxide is comparatively easily soluble in water, but its solubility decreases as the temperature rises; at 20°C . 100 volumes of water will dissolve approximately 38 volumes of this gas. This solution is strongly acid, and is in all probability a weak solution of sulphurous acid containing dissolved sulphur dioxide.

A polluted atmosphere does not usually contain more than a trace of actual sulphuric acid, but may contain a comparatively large quantity of sulphur dioxide, especially in the neighbourhood of some manufacturing centres or near burning coal-pit dumps, and in the case of large cities like London, Manchester, and Birmingham, this is contributed to by the great number of domestic fires. There

are other sulphur compounds found in the atmosphere of some towns—for instance, sulphuretted hydrogen (hydrogen sulphide, H_2S), and small quantities of the salts of sulphuric acid, such as sodium sulphate and ammonium sulphate, which remain suspended in the atmosphere until such time as they are washed out by rain. As has already been pointed out, soot contains a certain amount of free sulphuric acid, a fact which is important from the point of view of the decay of stone.

Now, when sulphuric acid acts upon the calcium carbonate of limestones, calcium sulphate is formed and carbonic acid is set free:



In the case of dolomite the action of sulphuric acid results in the formation of magnesium sulphate and calcium sulphate, and in the liberation of carbon dioxide. In these reactions there is a change in molecular volume, a fact already dealt with (p. 150), and this, with the evolution of carbon dioxide, cannot but help to disintegrate stone at the surface, especially when assisted by the chemical action. It should be noted that whilst calcium sulphate is soluble in water, it is only slightly so compared with magnesium sulphate, 33·8 parts of which are dissolved by 100 parts of water at 15°C . This means that in the case of dolomites exposed to the action of sulphur acids, not only will the stone suffer from the combined effects of increase in molecular volume and growth of crystals, but also from a weakening of the structure owing to the rain very rapidly washing away the changed magnesium constituent of the stone. A fact which must not be overlooked is that some of the limestones as well as some of the sandstones contain between 3 and 4 per cent. of magnesium carbonate.

The action of sulphuric acid on calcium carbonate is liable to slow down in speed after a time owing to the precipitation of calcium sulphate on the surface, and if this substance is not removed by rain-water or other means a more or less protective coat will be formed. This condition

is liable to occur in those parts of a stone elevation which are protected to a large extent from showers of rain, but which allow moisture to condense upon them from fogs, mists, and highly saturated atmospheres; this water, as the result of atmospheric pollution, contains sulphur acids. The under portions of string courses, mouldings, cornices, and other members may be quoted as examples. After a while soot accumulates on these positions, and this assists in the binding of the already formed calcium sulphate and that which may continue to form very slowly from time to time until the accumulation of soot prevents it altogether. When this condition has been reached, it is usually the case for a solution of calcium sulphate to be washed from the more exposed portions of a member, and this, on running over the protected and now very sooty portion, remains for a while, thus allowing some of the solvent (water) to evaporate, and causing the precipitation of a portion of the contained calcium sulphate. A continuation of this process results in the formation of the scallop-like incrustations which are so frequently seen on the under-side of projections in some parts of stone buildings.

Hydrochloric Acid (HCl).—This acid is sometimes found in the polluted atmospheres of manufacturing cities or towns, and, like sulphuric acid, it very readily attacks calcium and magnesium carbonates, setting free carbon dioxide in both cases.

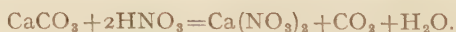


The calcium or magnesium chlorides which are formed are exceedingly soluble in water, and this fact will make it quite clear why, if limestones or dolomites are subjected to the action of this acid for any length of time, the surface decay becomes very rapid. Hydrochloric acid has a very detrimental action upon sandstones the sand grains of which are bound very largely by dolomite—for instance, the red and white Mansfield stones—and it will materially assist in the decay of those sandstones which have as subsidiary

binding materials calcium and/or magnesium carbonates or dolomite. It will be interesting to note the fact that the action of hydrochloric acid varies not only according to the nature of the stone, but also to its kind. The following results obtained during some experiments made in 1923 will illustrate this point. One-inch cubes of the stones were taken and kept surrounded by the moist vapours of hydrochloric acid for one month, and after this treatment they were washed thoroughly to remove the calcium chloride formed by the action of the acid on the calcium carbonate of the stones. They were then dried and carefully weighed under the same conditions as before treatment.

<i>Ancaster Stone (Free Bed).</i>	<i>Portland Stone (Whit Bed).</i>
Experiment A. 13·86 per cent. loss.	4·15 per cent. loss.
Experiment B. 6·65 ,, ,,	7·32 ,, ,,

Nitric Acid (HNO_3).—This acid does occur occasionally in the free state in the atmosphere in the neighbourhood of some manufacturing centres, but as a rule it is combined with ammonia as ammonium nitrate. The action of this compound on stone is similar to the chloride. Nitric acid itself is an active body which will dissolve calcium or magnesium carbonates rapidly, forming calcium or magnesium nitrate, both of which are very soluble in water. The reaction upon calcium carbonate is expressed as under:



The Phenols.—Undoubtedly there is a small quantity of these substances in the soot which is formed from the burning of coal in domestic fire-grates, but it is a debatable matter as to whether they act chemically upon the ingredients of some of the building stones. So long as the carbonates (magnesium and/or calcium carbonates) are present as such, then chemical reaction will not occur, but if calcium hydrate is formed, as indicated on p. 173, and phenol or carbolic acid is present (this substance being soluble in water), then there is a possibility of a chemical reaction taking place.

The quantity of phenol and its congeners present in soot being so small—and the same may be said of the amount of free calcium hydrate in weathering stone—then the actual decay produced by these substances, if any at all, will be so small as to be almost negligible. With the exception of the action of the free mineral acid and ammonium salts in soot, the damage done by this substance is the result of physical rather than chemical action.

Carbolic acid or phenol (C_6H_5OH), whilst not an acid in the accepted sense of the term, has the power of combining with hydrates and thus forming salts called phenolates; calcium phenolate is soluble in water. The higher phenols do not readily form combinations of this sort, but are liable to contribute towards the stickiness of soot.

Certain Plant Acids.—There are certain of the lower types of plant life, such as the lichens, which find a habitat upon building stones. The lichens are symbiotic organisms consisting of higher fungi and unicellular or filamentous algæ living in intimate connection. It appears that the fungi are nourished saprophytically from the organic matter produced by the algæ, which in return receive from the fungi inorganic substances and water, and possibly some organic matter. During this symbiotic manner of living, the lichens secrete certain materials which contain a number of acid bodies. These are able to dissolve inorganic matter, and thus provide the inorganic salts which are necessary for the existence of the dual organism, and it is these acid bodies which exert a destructive action upon the limestones and those sandstones which contain as natural binding material dolomite or calcium carbonate. Undoubtedly this is a contributory cause of the decay of certain stones, but it is certainly a minor one, and in any case the growth of lichens on stone should not be encouraged.

Apparently those lichens which find a habitat upon stones show some preference in regard to the type of stone upon which they choose to exist. For instance, *Bilimbia coprodes* prefers siliceous stones, whilst *Verrucaria calcarea* shows a

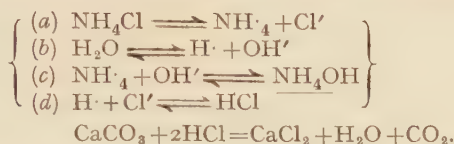
preference for calcareous stones, and *Amphoridium dolomiticum* chooses as a rule the dolomites.

(b) **Action of Chemical Salts.**—*Ammonium Chloride* (NH_4Cl).—This salt may be deposited on the stone in buildings in conjunction with soot or in the free state by being washed out of the atmosphere by rain. It is chiefly a product of the burning of coal.

Ammonium chloride is formed by the combination of hydrochloric acid and ammonia, and it is, speaking comparatively, a very soluble salt, 35.2 parts dissolving in 100 parts of water at 15°C . If an aqueous solution of ammonium chloride is boiled, ammonia escapes and the solution becomes distinctly acid, and then it acts strongly upon some metals, and especially iron. It is also a fact that a cold aqueous solution of ammonium chloride will chemically react upon iron and copper and promote corrosion of these metals. Now, as this is so, then it is not unreasonable to suppose that a solution of ammonium chloride, even at ordinary temperatures, will react with the calcium carbonate of limestones, the dolomite of the magnesian limestones or the calcareous binding material of some of the sandstones; as a matter of fact, experiment has proved this to be the case. If a blue litmus paper is wetted with an aqueous solution of ammonium chloride it shows a slight acid reaction at first, but there is a gradual increase until a strong acid reaction is indicated, the litmus paper developing a very marked red colour. A film of ammonium chloride solution will become more acid than a bulk quantity.

When ammonium chloride is dissolved in water it is ionized to a small extent (about 0.75 per cent.) into ammonium (NH_4) and chlorine (Cl') ions. Water is also very slightly ionized into hydroxyl (OH') and hydrogen (H') ions. On this account a small quantity of hydrochloric acid will be present (which accounts for the slight acid reaction of a cold, unboiled ammonium chloride solution), and this acid will act upon the calcium carbonate, forming calcium chloride (CaCl_2), which is very easily washed away by rain.

The reactions which take place may be expressed thus:

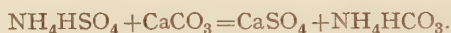


The following experiment was conducted on three stones—viz., Portland (whit bed), Ancaster (free bed), and Park Nook—to find out the corrosive effect of a solution of ammonium chloride on them. A 15 per cent. aqueous solution of this salt was prepared and $\frac{1}{2}$ cube inch of each of the stones immersed in it for a period of nine months, arranging matters so that evaporation could not take place. At the expiration of this time the stones were removed, washed with water until free of ammonium and calcium chloride, dried, and weighed. The loss of weight suffered by each stone is given under:

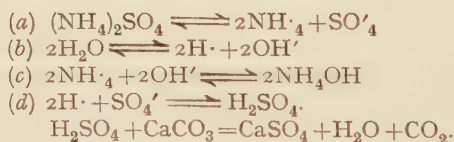
<i>Portland (Whit Bed).</i>	<i>Park Nook.</i>	<i>Ancaster (Free Bed).</i>
1.41 per cent.	1.06 per cent.	0.70 per cent.

Ammonium Sulphate, $(\text{NH}_4)_2\text{SO}_4$.—This chemical substance can be formed by a reaction between sulphuric acid and ammonia, and it is brought into contact with stone by the deposition of soot or by being washed out of the atmosphere by rain. It occurs in the form of rhombic crystals, and it is very soluble in water—for instance, 74.2 parts will dissolve in 100 parts of water at 15° C. Its aqueous solution on evaporation loses part of its ammonia and becomes acid. When this salt is dissolved in cold water the solution reacts neutral to litmus, but if a blue litmus paper is wetted by it and allowed to dry in the atmosphere it gradually becomes reddened, which seems to indicate that during the evaporation of the solvent (water) some ammonia escapes with it and an acid salt of ammonium sulphate is formed. There is no doubt about the definiteness of this test, for if a blue litmus paper is made slightly alkaline after wetting, by holding it in gaseous ammonia and then finally dipped into a

solution of ammonium sulphate and allowed to dry, as evaporation proceeds the paper will turn red, as just described. A solution of this salt at 90° F. gives an immediate reaction to litmus, and a solution at a temperature of 190° F. gives off small quantities of ammonia vapour and becomes very distinctly acid. All this will indicate that ammonium sulphate possesses the power when in solution (in the presence of water on wet stone) of reacting on the calcium carbonate or dolomite, forming calcium sulphate and/or magnesium sulphate. In one reaction calcium nitrate is formed (see p. 200), but it is also probable that the following reaction may take place if the acid salt is present:



It should be noted also that ammonium sulphate is subjected to ionic dissociation when dissolved in water, giving NH_4^+ and $\text{SO}_4^{'}$ ions, and this, with the slight ionization of the solvent (water), will produce a small quantity of sulphuric acid, thus:



It will be seen here that whichever reaction takes place the ultimate result is the production of calcium sulphate, a substance which, as already pointed out, is comparatively easily dissolved in water and therefore washed away, and which under suitable conditions can produce physical disintegration by the growth of its crystals. That ammonium sulphate does attack calcium carbonate (calcite) has been proved experimentally, and one example is given on p. 200. Other workers and the author have found ammonium sulphate in decaying stone of many kinds, such as Portland, Bath, Anston, Huddlestone, red Mansfield, and several of the sandstones.

Sodium Chloride.—This is a neutral salt which crystallizes in the form of cubes and which is soluble in water to the

extent of 35 parts per 100 at 15° C. It is most unlikely that this salt in the pure state ever reaches the surface of building stones when in position in a structure, but mixed with other substances in atmospherically carried sea spray it comes in contact with the stone in those structures on and near the sea coast. The atmosphere near the coast may contain small or large quantities of sea salts, according to the time of the year, and measured in terms of sodium chloride the amount may vary from 0.35 part per 100,000 to as much as 34 parts per 100,000.

The following particulars are interesting in this connection: At Rothamsted the average rainfall is 31.65 inches, and the amount of sodium chloride in the rain-water is 33.1 parts per 100,000, which is equivalent to a distribution of 24 pounds of this salt per acre. Similar particulars for Cirencester are: Average rainfall, 33.31 inches; amount of sodium chloride in the rain-water, 53.5 parts per 100,000; equivalent distribution per acre, 40.3 pounds.

Whilst salt is the chief ingredient in the solid matter of sea water, it is accompanied by several others, as is shown in the analysis of sea water given below:

TABLE X.

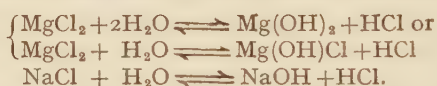
Sodium chloride	2.700	} 0.815	} 3.515
Magnesium chloride	0.360		
Magnesium sulphate	0.230		
Calcium sulphate	0.140		
Potassium chloride	0.080		
Calcium carbonate	0.003		
Magnesium bromide	0.002	}	
Water	96.485		

From this table it will be seen that the sodium chloride is associated with magnesium chloride, a very deliquescent substance, and also magnesium and calcium sulphates, both of which, as has already been pointed out, cause injury to many types of stone owing to the growth of their crystals.

Careful observations made by several investigators indicate that the decay of certain stones can be produced by

the crystallization of the salts from sea spray on and just below the surface. This is specially the case with those stones which do not allow free crystallization to take place, but the author has seen localized decay of Portland stone brought about by this cause.

As sodium and magnesium chlorides are slightly hydrolyzed when dissolved in water, with the result that a small quantity of hydrochloric acid is formed, then the possibility of a slight corrosive action on the stone exists. The action may be very slight, but nevertheless not insignificant; combined with the time factor it may make itself felt in such a manner as producing a weakening effect only sufficient to assist the physical action of crystal growth and its consequent disintegration. What happens when these salts undergo hydrolysis¹ is indicated by the equations given below:



Observations made by the late Charles Darwin² on the disintegration of shell beds in that part of the Isle of San Lorenzo facing the Bay of Callao have shown that the calcite constituent of the shells is being decomposed by the sodium chloride in the sea salt left by the evaporation of sea spray. This type of decay is hardly likely to occur to any great extent in this country; it is possible in those positions in which the sodium chloride cannot be easily washed away.

It has been found that the solvent action of water containing carbonic acid is increased in regard to calcium carbonate, calcium sulphate, and some of the calcium silicates if sodium chloride or magnesium chloride is dissolved in it, so that it will appear that limestones and certain sandstones occupying positions in buildings which allow them to be more or less constantly wetted with water con-

¹ By "hydrolysis" is meant the action which takes place between a salt and water whereby free base and free acid are formed.

² See "Journal of Researches during the Voyage of H.M.S. *Beagle*."

taining these salts will suffer from increased surface decay owing to augmented solvent action.

Solution.—It has already been mentioned on p. 150 that opinion is divided as to whether the process of solution is a chemical or physical one, but whichever it is a solvent is necessary, and in the subject under consideration this is water, not pure, but chiefly in the form of rain. Mists and other forms of condensed atmospheric moisture will act somewhat similarly to rain.

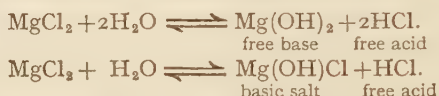
Careful experiments have shown that many substances possess a different solution tension or solution pressure for each solvent with which they may be brought into contact, and it is inferred that all substances exhibit this property. Solution pressure is briefly and simply explained as follows:

When a substance (say a crystal) is placed in a solvent, such as water, some of its particles become detached from the surface and enter the solvent. After a period of time a number of these detached particles come into contact with the surface of the substance again and are there retained. This process goes on until the same number of particles leave the surface of the substance as are returned to it; equilibrium is set up. When this condition of equilibrium is reached a saturated solution is the result, and the dissolved substance is exerting a pressure which is equal to the pressure exhibited by the solid at its surface; this latter is known as a solution tension or solution pressure. It should be noted that, in addition to the solution pressure of a substance, it is possible that the solvent exerts an attractive force on the particles at the surface of this substance.

It has been suggested by certain workers that many of the reactions which occur when substances are in solution may be considered without taking into account the active part the solvent itself may play. It has been found, however, that in a number of cases the solvent actually does exert some influence, and it is quite possible that in all cases, whilst it is not possible to demonstrate it, there is some sort of interaction between a solvent and the substance which

it has dissolved. There is experimental evidence of the formation of compounds by the combination of molecules of the solvent and those of the substance dissolved.

There are a large number of substances which, when dissolved in water, are hydrolyzed or ionized. By hydrolysis is meant that the water and the substance dissolved in it interact, with the result that a free acid and a free base, or an acid and a basic substance, are formed. For example:



By ionization is understood the splitting up of a substance, when it is dissolved in water, into atoms or groups of atoms known as radicals. A molecule on ionization will furnish two kinds of ions which will carry equal and opposite charges of electricity. The following ionic equations will illustrate the case:



When a substance dissolves in water only a portion of it—viz., that which has been changed into ions—becomes active; this activity is expressed by the term “activity coefficient,” which is the ratio of the number of so-called active molecules (the part of the substance which has been changed into ions) to the sum of the active and inactive molecules. The following table gives the activity coefficient of a few of the substances which come under the purview of the subject of decay of stone. *One gramme molecule¹ of the substance is dissolved in 10 litres of water.*

Sodium hydroxide	..	..	..	..	0.88
Potassium hydroxide	..	..	..	..	0.93
Ammonium hydroxide	..	..	..	..	0.01
Sodium chloride	..	..	..	..	0.82
Ammonium chloride	..	..	..	..	0.84
Hydrochloric acid	..	..	..	..	0.90
Nitric acid	..	..	..	..	0.92
Sulphuric acid	..	..	..	..	0.60
Sulphurous acid	..	..	..	..	0.14

¹ The molecular weight of a substance in grammes.

Temperature influences the solubility of all substances, and, speaking generally, the higher the temperature the more of a substance will dissolve; there are some substances which decrease in solubility when the temperature of the solvent is raised, and among them are one or two compounds which are associated with the subject under consideration—viz., calcium hydroxide and calcium sulphate. The differences in solubility are shown under:

	0° C.	100° C.
Ca(OH) ₂ ..	0·17	0·08 part per 100 parts of water.
CaSO ₄ ·2H ₂ O ..	0·241	0·222 „ „ „ „ „

The solubility of a substance in water or other solvents is affected not only by differences in temperature, but to an extent by the size of the particles of that substance. According to Dr. H. Bassett¹ the solubility is practically independent of size if the particles are greater than 0·02 mm. in diameter, but there is a well-marked increase when they become much smaller than this. Hulett,² dealing with calcium sulphate, states there is no difference in the solubility of this salt in water until the radius of the crystals is less than 2μ .³ The changing from 2μ to $0·3\mu$ brings about an increase in solubility of nearly 20 per cent. It should be noted also that, usually, the smaller the particles of a substance the more rapidly does it dissolve, and this is due to a very large extent to the greater surface exposed to the action of the solvent. It is likely that this may partly account for the more rapid decay of the finer portions of Portland and other similar stones, with the result that the fossils and veins of calcite weather in relief.

Sir J. J. Thompson, when dealing with potassium sulphate, found that the solubility of this salt was greater when the solution was contained within the pores of a substance such as meerscham than when the liquid was in bulk. Is it

¹ "Colloid Problems in Analytical Chemistry." Fourth Report on Colloid Chemistry, p. 6. H.M. Stationery Office, London.

² *Zeit. Phys. Chem.*, 37, 385 (1901).

³ $A\mu$ is 0·001 mm., or about $\frac{1}{25,000}$ inch.

possible that the solubility of calcium carbonate and calcium bicarbonate in the "pores" of a stone during decay is increased for the same reason? A fact worthy of notice is, that in the presence of pores the vapour of a liquid which will wet the substance containing the pores has what is known as its equilibrium pressure lowered, and it becomes easy for condensation to take place in the pores even if the atmosphere is not saturated with vapour. This, and the fact that large drops of liquid will grow at the expense of small ones, and in doing so produce a decrease of surface tension (and, therefore, an increase in flow), may contribute towards the rapidity of solution.

It has been found that water is adsorbed by quartz at 30° C. from an atmosphere within 1 per cent. of saturation, and the thickness of this water film is approximately $26.6\mu\mu$.¹ It is possible that other constituents of stone adsorb water under similar conditions, and this fact may account for the somewhat persistent moist state of stones when exposed to the atmosphere.

It is a well-known fact that all substances are soluble in pure water, but some so very slightly that for all practical purposes they are considered as insoluble. Before dealing with rain-water, it will be convenient to consider the solvent action of pure (distilled) water on the constituents of the various building stones. Apparently very little work has been done on this subject up to the time of writing, and therefore the amount of information forthcoming must necessarily be small. Experimentally it has been found that the following substances are more or less soluble in pure water in amounts as given:

- (a) Calcium carbonate: 100 parts of water at 15° C. dissolve 0.0018 part.
- (b) Magnesium carbonate: 100 parts of water at 15° C. dissolve 0.0106 part.

In order to see the effect of the passage of distilled water through limestones and the ultimate result when it evaporated

¹ A $\mu\mu$ is 0.001 μ , or 0.000001 mm. ($\frac{1}{25,000,000}$ inch approximately).

from a surface exposed to the atmosphere, three small rectangular blocks of different limestones—viz., Portland, Ancaster, and Park Nook—were placed in distilled water at an angle of 45 degrees, so that one horizontal edge and a small portion of each surface were exposed to the atmosphere, thus allowing the water which penetrated the stones by capillary action to evaporate from this spot. Twenty-four hours after the commencement of the experiments it was found that salts appeared all along the edge in the case of the Ancaster stone, a slight trace in the case of the Portland stone, and a very slight trace on one corner in the case of Park Nook. It was noted that whilst the salts which had crystallized from the Portland and Park Nook stones were whitish in colour, that from the Ancaster stone was brownish in colour. After a month's interval the salts in each case had increased considerably, and they had also, in the case of Portland and Park Nook, become foxy-red and light brown in colour respectively. The experiments were continued for nine months, and it was found that there was very little increase in the amount of salts after the first month. The salts were allowed to dry and then carefully removed and submitted to a qualitative examination, with the following results:

The salts from Portland stone and Ancaster stone were found to be partly soluble in cold water, and the water-soluble portion showed a slight trace of chlorides, a rather larger trace of sulphate, some calcium, and a fairly heavy sodium flame. The insoluble portion dissolved in dilute hydrochloric acid on warming, with effervescence. It was found to contain a trace of sulphate of calcium, a little iron, and also some calcium carbonate.

The salts from the Park Nook stone were very small in quantity compared with those obtained from the other two stones, and there was not sufficient insoluble in water to make a proper examination. The soluble portion on testing showed the presence of calcium, sulphates, a trace of chlorides and of sodium, and the absence of iron in the water-soluble form.

It was noted that after the experiments the surfaces of the stones which had been exposed to the atmosphere were in each case discoloured. In the case of the Portland stone the stain was light brown with a slight red undertone, and it covered almost the whole surface from which evaporation had taken place; it was also deeper along the edge. The stain on the Ancaster stone was reddish-brown, and it was very concentrated in proximity to the edge which was exposed to the atmosphere. The Park Nook stone was stained a deep reddish-brown to a width of approximately $\frac{1}{4}$ inch from the edge proceeding inwards.

The results of these preliminary experiments, which are sufficiently important to warrant their being followed up on a larger scale, indicate that pure water can dissolve, even if only slightly, the constituents of the limestones (some of which may be in the form of quarry sap salts), and assisted by capillary action bring them forward to the surface, where they have the opportunity of crystallizing, and could in some instances assist in decay. Pure water also produces, by capillary action and evaporation, a concentration of iron salts on the surface of stones, thus producing stains.

If pure water can act upon some stones as just indicated, if even only slowly, how much more rapid will this action be when the water contains impurities dissolved out of the atmosphere.

Rain-water contains approximately 2.5 c.c. of gases per 100 c.c., and they occur usually in the proportion of: nitrogen, 64 per cent.; oxygen, 34 per cent.; carbon dioxide, 2 per cent. Carbon dioxide is more soluble in water than the other gases, and on this account it is contained in rain-water in a proportion about thirty-five times greater than in the atmosphere; in fact, the rain concentrates the carbon dioxide, producing carbonic acid in an active state ready for action on any limestone upon which it may fall. From this it will be seen that rain-water is actually a carbonated water, or, in other words, it will contain a small percentage of carbonic acid. It is also possible for it to contain traces

of sulphuric acid, hydrochloric acid, or nitric acid, and also the ammonium salts of these acids, especially when it falls in the neighbourhood of manufacturing cities and towns.

It has been found by the Rogers Brothers¹ that carbonated waters at a temperature of 60° F. will react on naturally occurring silicates, and in the case of hornblende, which was subjected to the action of carbonated water accompanied by rapid agitation for forty-eight hours, there was yielded to the water 0.08 per cent. of silica. R. Müller² investigated the action of carbonated water on a number of mineral silicates, and obtained the results shown in Table XI. The experiments extended over a period of seven weeks.

TABLE XI.—SOLUBILITY OF MINERALS IN CARBONIC ACID.

<i>Mineral.</i>	<i>SiO₂.</i>	<i>Al₂O₃.</i>	<i>K₂O.</i>	<i>Na₂O.</i>	<i>MgO.</i>	<i>CaO.</i>	<i>P₂O₅.</i>	<i>FeO.</i>	<i>Total Per- cent- ages.</i>
Adular ..	0.1552	0.1368	—	—	—	—	—	trace	0.328
Oligoclase	0.237	0.1713	—	2.367	—	3.213	—	trace	0.533
Hornblende	0.419	trace	—	—	—	8.528	—	4.829	1.536
Magnetite	trace	—	—	—	—	—	—	0.942	0.307
Apatite ..	—	—	—	—	—	2.168	1.822	—	2.018
Olivine ..	0.873	trace	—	—	1.291	trace	—	8.733	2.111
Serpentine	0.354	—	—	—	2.649	—	—	1.527	1.211

Whilst the action of carbonated waters on sandstones containing felspar (oligoclase) fragments and other silicates will be very slow, it is nevertheless sure, and undoubtedly in time must weaken the strength of the structure of the stone in a slight degree, but in any case sufficient to assist other and more vigorous and destructive agents to effect their undesirable actions; and let it not be forgotten that in some sandstones the subsidiary binders are calcium

¹ *American Journal of Science*, vol. v. (1848).

² "Untersuchen über die Einwirkung des kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine, Tschermaks Min. Mittheilungen" (1877), p. 25.

and/or magnesium carbonates, and the action of carbonated water on these substances is somewhat more energetic.

The action of carbonated water, or, in other words, a solution of carbonic acid, on the limestones and dolomites, has already received attention (see pp. 173-174).

There is no doubt that the continual saturation with rain-water, combined with capillary action and evaporation from the surface when conditions allow of this process, removes not only the soluble salts in the natural binding materials of both the limestones and sandstones, but, coupled with chemical action due to the active impurities contained in the water and the solution of the resulting new compounds formed, results in a very important contributory cause of the disintegration of stone. This process is very marked in the case of the magnesian limestones and the dolomitic sandstones, for in the decay of these stones the very soluble salt magnesium sulphate is formed, and after formation it is removed by leaching due to the soaking in of rain-water, with the result that the strength of these classes of stones is weakened considerably.

Whilst dealing with the subject of solution it will not be out of place to consider briefly why in the weathering of many building stones the chemical compositions of which are alike, being almost pure calcium carbonate, some portions decay more rapidly than others. The reasons are not easy of explanation; they are in all probability physical rather than chemical. Among them may be mentioned:

- (a) The effect of crystalline structure and its bearing on the rate of solution.
- (b) The extent of the solution pressure of the substance in regard to water.
- (c) The effect of the amount of surface per volume of mass (the extent of reaction surface) exposed to the corrosive agent or agents.
- (d) The ease by which the attacking substance can be removed by rain or other means.
- (e) Presence of impurities in the crystals, and especially those of the matrix.

As an illustration, weathered Portland stone provides a very good one, as it generally shows a large quantity of fossils standing out in relief, indicating that these portions of the clastic are more resistant to attack than the other portions, and also the matrix.

In regard to (*a*), if the fossils of Portland stone are examined carefully they will be seen to consist of a mass of crystals of calcite very closely packed together. It is a fact that the physical properties of a crystal are not the same in all directions, which means that in one direction it will be somewhat more soluble in acid than in another. If, therefore, the average exposed portions of the crystals composing the fossils are more resistant than the non-exposed portions, then the rate of solution of the fossils will be somewhat reduced. Also, different forms of crystal structure behave differently in regard to the action of acids or ionizable salts upon them, and there is the possibility that the crystalline form of calcite existing in the fossils is different from that of the crystals in the other portions of the clastic, and also of the matrix. To dismiss a matter of this kind with the remark that the crystals of the fossils are more compact and therefore more resistant, is unscientific and retards progress; this subject is worthy of careful investigation by those who are fortunate enough to possess the knowledge, time, and facilities. It has been found in the weathering of St. Aldhelm Box and Monk's Park stones that the outer layers of the ooliths are far less resistant than their nuclei, and that the matrix, which is crystalline, is also more resistant than the outer layers of the ooliths.

Dealing with (*b*), the matter of solution pressure is in all probability governed to a certain extent by (*a*). An explanation of solution pressure has been given on p. 185. Now, the greater the solution pressure of a substance the more particles of that substance will go into solution in the solvent (water) covering it, and it is these particles which are acted upon by an ionized acid or salt—for instance,

sulphuric acid or ammonium sulphate—and the new substance formed is then carried away or deposited on the surface according to existing conditions. Should, therefore, the solution pressure of the crystals of calcite composing the fossils be less than that of the calcite composing the other portions of the clastic and also the matrix, then it will weather away more slowly.

Considering (c), we may again take for our illustration decayed Portland stone, comparing the weathered-out fossils with the finer weathered-back matrix. It will be quite obvious to the reader that if a given mass of a substance be divided into a number of small portions, then the amount of external surface (reaction surface) will be greater than before division. Now, in a given volume the amount of surface exposed by that of the fossiliferous portions of the Portland stone, compared with that of the surface exposed by a similar volume of the ooliths and the fine material of the matrix, will be far less. As chemical reaction takes place only at the surface of a mass, it will be clearly seen that the greater the amount of surface exposed to the attacking substance the more rapid will be the decay of that mass. It follows from this argument that as the finer material of Portland stone offers a greater surface to the attack of corrosive substances than the coarser fossiliferous material, then the former will decay more rapidly than the latter.

With reference to (d), we may again use decayed Portland stone to illustrate the explanation. On examining the weathered-out fossils it will be noticed that they possess comparatively smooth non-porous surfaces, which can be very easily washed clean by rain, and will therefore retain with far less difficulty any corrosive material, whilst the softer, rougher, and more porous portions of the stone will absorb deleterious materials and hold them somewhat tenaciously, the removal of them by rain being less easy.

With reference to (e), it is a well-known scientific fact that impurities in a substance either increase or decrease the rate of chemical action, and as a typical illustration of this

may be cited the more rapid corrosion of iron in the event of it containing traces of manganese sulphide, and the less rapid corrosion of the same metal if it contains a small quantity of chromium or nickel. The phenomena relative to the action of impurities on the solubility of various chemicals have been studied a little, and the work already done is not in any way related to calcite or other forms of calcium carbonate; it is a research worthy of attention.

Hydration.—This process, which constitutes the addition of water molecules to chemical substances, very often accompanies the process of oxidation, and in regard to the disintegration of rock masses in the earth is one of great importance. It is highly probable that in the decay of some of the building stones it is a factor of more importance than is generally supposed. In the process of hydration heat is liberated and there is increase in molecular volume, and with reference to the subject under treatment the latter is more important than the former. Should a stone which contains material prone to hydration be porous, then it is possible that this process may proceed to some depth below the surface, and result eventually in decay in the form of crumbling to powder.

Stones which contain anhydrous ferric oxide are liable to suffer on account of this oxide changing, by the process of hydration, into forms of hydrated ferric oxide (laterite), with increase in molecular volume, creation of pressure, and consequent slow disintegration. The writer has had experience with a stone from the Cuddalore sandstone deposits in India, called Tada stone, which, although very hard, is slowly disintegrated by the hydration of the ferric oxide in the tiny but numerous veins which run throughout its mass.

Oxidation.—Speaking broadly, as far as building stones are concerned the amount of decay brought about by oxidation¹

¹ Oxidation is a process which involves the addition of oxygen, and the raising of a substance from a lower to a higher state of oxidation, or it may be the removal of hydrogen.

is comparatively small; most of the building stones contain very little which is oxidizable.

The presence of iron disulphide in the form of marcasite (FeS_2) may cause trouble, because upon oxidation there is not only an increase in molecular volume due to its change in state, but one of the resulting products may be sulphuric acid, which will cause rapid local decay. What appears to happen is that the disulphide is converted into ferrous sulphate (green copperas), and traces of sulphuric acid are formed at the same time, and the latter will act upon the surrounding calcium carbonate of the stone, whilst part of the former is often washed away and another portion oxidized to ferric oxide. Marcasite occurs in several of the chalk stones, in some of the dolomites, and also in several of the Palæozoic limestones.

Certain of the sandstones contain ferrous carbonate, and this substance, when exposed to the weather, is oxidized into limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), producing a change in molecular volume, in this case also an increase. Iron in the form of magnetite ($\text{FeO} \cdot \text{Fe}_2\text{O}_3$) occurs in some of the metamorphic rocks, serpentines, etc., and is susceptible to further oxidation. In this instance the ferrous oxide (FeO) portion of the magnetite molecule is converted wholly into ferric oxide, with an increase in molecular volume and consequent disintegration of the portions of stone in the immediate neighbourhood of this mineral. Another mineral which occurs in certain building stones, such as Kentish Rag and some other stones which possess a greenish tint, is glauconite, which is essentially a hydrous silicate of iron and potassium. This substance is prone to oxidize under certain atmospheric conditions, the iron portion being converted into ferric oxide, thus producing reddish spots, and ultimately local disintegration.

Whilst oxidation is a cause of local decay of some of the building stones, it is not one of great importance as far as general decay is concerned, but if a stone is employed which contains small quantities of oxidizable substances, and these

are in the exposed face, there is a liability to produce local trouble in the form of unsightly stains.

Deoxidation¹ (Reduction).—This process is much less likely to cause decay in building stones than oxidation, but should stones be used which contain ferric iron, and fixed in places in which they will come in contact with organic acids and at the same time be continually wetted, then the ferric oxide may be reduced or deoxidized and thereby changed into the ferrous state, with the consequent reduction in molecular volume and the bringing about of local disintegration. There are quite a number of stones which contain ferric iron in one form or another.

The conditions under which deoxidation is most likely to take place are chiefly those in which the stones are used for fountains, and plinths or other parts of buildings below or very close to ground level, or in situations where organic matter can gain easy access, but when once in position may be difficult of removal, or in bridge abutments surrounded by contaminated waters.

Action of Bacteria.—The part which micro-organisms (bacteria) play in the decay of rocks was discussed by A. Müntz in 1887, also by Winogradsky and Schlosing, and later by Dr. Tempest Anderson in 1910, and the subject was studied mainly from the point of view of the formation of soil. Recently J. E. Marsh, F.R.S.,² of Oxford, has suggested that bacteria may also cause decay in building stones, and in the opinion of the author this matter should receive careful consideration.

A. Müntz³ states that the bare surfaces of rocks, even at great elevations (*i.e.*, near the summit of mountains), yield large numbers of bacteria of the nitrifying type. The Pic Pourri of the Bernese Alps may be cited as an example.

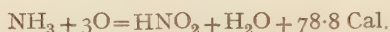
¹ This process is just the opposite to oxidation—viz., the removal instead of addition of oxygen from a substance.

² "Suggestions for the Prevention of the Decay of Building Stone." Basil Blackwell, Broad Street, Oxford.

³ *Journ. Chem. Soc.*, 1887, Abstracts, 1135.

This peak is of friable calcareous schist, superficially decomposed, and throughout the decomposed material nitrifying bacteria are distributed. Experiments made by Müntz show that these organisms are able to live and produce nitrate, and also to accumulate the element carbon without any other food than the mineral matter of the rocks *and small quantities of ammonia and alcohol vapour*, if surrounded by a moist atmosphere.

Winogradsky¹ found these bacteria are able to obtain carbon from the mineral carbonates by the energy liberated during the oxidation of ammonia to nitric acid. This worker states that the nitrosomonas oxidize ammonia to nitrous acid:



and the nitromonas oxidize the nitrous acid to nitric acid:



According to Marshall,² "These oxidation processes yield a certain amount of energy which enables the bacteria to build their cells from carbon dioxide, ammonia, and certain mineral salts. Without ammonia or without nitrous acid respectively, these bacteria cannot grow for lack of energy; they would be like a plant without light. It is evident in this case that the food for energy is also used to some extent as food for growth. The nitrogen necessary for the bacteria is supplied by the ammonia or the nitrous acid." From these remarks it will be quite clear to the reader that ammonia or ammonium salts or substances which are capable of decomposing into ammonia or ammonium compounds—for instance, the proteins—must be supplied to these bacteria in order that they may live, and in the case of the proteins, other species than the nitrifying bacteria are necessary to bring about the primary decomposition. Bird droppings may be a possible *local* source of nitrogen; pigeon excreta, for instance, contains approximately 1.8 per cent. of organic nitrogen.

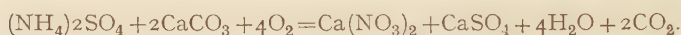
¹ *Journ. Chem. Soc.*, 1890, Abstracts, 1180.

² "Microbiology," 2nd edition, p. 146.

To promote nitrification the presence of a small quantity of moisture is necessary, together with alkaline salts such as calcium or magnesium carbonate, or the carbonates of potassium or sodium. These bodies will neutralize the organic acids set free by the bacteria, and therefore keep down undue acidity, which opposes bacterial growth. In the case of the limestones and many of the sandstones the calcium or magnesium carbonate (or both) which is present may provide the necessary substance for neutralization. It will seem, therefore, that if the right species of bacteria found their way on to the stone and the necessary food is provided for them, say, in the form of ammonium salts or protein matters, then the formation of nitrous and nitric acid will eventually take place. To decompose protein substances into ammonia and ammonium compounds bacteria such as *B. mycoides* or *B. proteus* are necessary, and to oxidize the ammonia into nitric acid, the Nitrosomonas, Nitrosococcus, and Nitrobacter are needed. Strong sunlight suspends some of these processes, and will eventually destroy the organisms. Whilst the possibility may exist of all these conditions being fulfilled, the probability of bacterial action causing the decay of stone, especially in towns and cities, is not very great; and this will be reduced very considerably by the presence of soot which comes in contact with the stone under town conditions, and which is distinctly hostile to most, if not all, types of bacterial life on account of the coal-tar constituents which it contains. In the opinion of the author the action of bacteria in causing decay of stone is doubtful, and even if it does occur in isolated cases, the amount of decay produced by the nitric acid formed is very little when compared with that caused by deleterious substances in the atmosphere and in rain-water. To arrest bacterial action, if it is present, and to prevent it from occurring, if it ever will, by treating stone with a caustic soda solution, as suggested by Marsh, is simply "playing with fire," as will be seen on reference to p. 201; in fact, the use of this substance will assist

eventually in the decay of the surface of the stone treated by it.

J. E. Marsh suggests that the presence of nitrates in stone is an indication of bacterial action, or "life," as he puts it, causing stone to decay. With others, the author has found combined nitrogen in stone in very small quantities in the form of nitrates, and in many cases in larger quantities in the form of ammonium salts, and particularly the sulphate. The ammonium salts appear to be introduced into the stone directly or indirectly from polluted atmospheres, and most of the calcium nitrate is probably formed by a chemical reaction between ammonium sulphate and calcium carbonate:



It is a very simple matter to show that ammonium sulphate does react with calcium carbonate by placing a damp crystal of the sulphate, or a piece of cotton-wool saturated with a solution of this salt, on a crystal of calcite and then keeping in a damp situation. After a period of about two weeks, if the sulphate is washed off, the surface of the crystal will be found to be etched. The small quantity of calcium nitrate found in some stones may be due to the decomposition of organic (protoplasmic) material which originally constituted the living matter of shell-fish or other organisms, the shells of which now constitute a part of the clastic of the stone. Somewhat in support of this latter statement is the fact that crude petroleum occurs both in limestones and sandstones, and it contains nitrogen, the presence of which is due to the decomposition of organic material. There appears to be no reason why, when very small quantities of organic material containing nitrogen occur originally in the detritus from which these classes of rocks are formed, some of the nitrogen present should not, through a series of reactions, enter in combination with the calcium or magnesium also present, forming nitrates. Naturally it does not do to dogmatize in these matters, especially when dealing with the subject of the chemical reactions which

have taken place in a rock mass in the early geological ages, under conditions which are not known, but which can be only surmised; geo-chemistry is as yet in its early infancy.

It may be suggested by some that it is possible for nitrates to be introduced into certain stones from the soil and sub-soil which constitutes a portion of the overburden whilst the stone lies in the earth. The rain or other water which soaks into the soil will in its downward course dissolve and carry onward nitrates, and finally this solution will be absorbed by the stone beneath, and leave in it these salts as constituents of the quarry sap or quarry water. In considering this suggestion it must not be overlooked that the amount of nitrates in the soil at any given time is very small, and if a solution containing these substances is passed through soil, the tendency is for them to be removed from the solution by adsorption, so that if the overburden is very thick, then the amount of nitrates left in the water by the time it reaches the stone may be almost negligible; drainage water from soil contains only 0.0006 to 0.0014 part of nitrates per 100.

The facts that very small quantities of the oxides of nitrogen do exist in the atmosphere, and that nitrogen is found in rain-water in the form of nitrates, also in small quantities, must not be overlooked, for these will add their quota to the nitrates found in stone.

Hydrofluoric Acid and the Silicofluorides.—It is known to those who have made careful observations that these chemical substances do cause decay in certain types of stone, but as they are used by some with the idea of preserving stone, it is thought fit to deal with them, their properties, and their action upon stone, in the chapter on stone preservation (see p. 245).

Caustic Soda (NaOH) is a white substance, crystalline in character, very deliquescent¹ when exposed to the atmosphere, and it is easily soluble in water. Whilst dissolving in water it generates much heat. The solution reacts very

¹ Absorbs moisture rapidly from the atmosphere and eventually becomes liquid.

strongly alkaline, and is of a corrosive nature. Caustic soda very easily combines with acid substances, and on this account it is known as a strong base.

In addition to it being marketed under its legitimate name, caustic soda, it is sold and used under many disguises, both in name and nature, and is often mixed with various substances, both organic and inorganic, and this means that the architect, building contractor, and others who require the stonework (and also brickwork) of buildings cleaned and preserved, are often misled into recommending, or purchasing, or using these very dangerous substances owing to their nature not being perfectly understood, mainly because of the trade or fancy names employed as disguises. It will not be out of place here to introduce a word of warning and also advice to all those who at one time or another have buildings placed under their care, to avoid using for cleaning or other purposes any substance sold under a trade or fancy name without first of all knowing its composition and requesting from the manufacturer or user some sort of guarantee that the constituents will not injure the stone. There is no need to hesitate in placing caustic soda and its preparations among the most dangerous materials from the point of view of damaging stone (or brickwork).

Whilst the interaction between caustic soda and calcium carbonate (the chief chemical constituents of the limestones) is practically negligible, its physical action on various stones warrants most careful consideration owing to the injury which it causes. This type of action may be divided into two classes, the chief of which is the production of pressure due to changes in molecular volume and also to crystal growth (both having their origin in chemical action between the caustic soda and the impurities in the atmosphere), which results in exfoliation, or crumbling of the stone. The other and minor physical action is slight peptizing,¹ especi-

¹ To peptize means to transform a substance into a sol (a liquid colloid), or to disintegrate a substance into such small particles that they can form a colloidal solution.

ally in the case of those stones which contain local areas of very fine material, or current beds of a clay-like nature. Very little attention seems to have been given to this matter, but preliminary investigations made recently on the effect of caustic soda solutions on the finer portions of some types of building stones indicate a softening action and a tendency to form colloidal solutions. This means that the soft portions will be more easily removed by tools employed in cleaning after the use of this chemical, or by heavy rain if this occurs shortly after the caustic soda has been applied, and it means also that a comparatively considerable amount of the caustic soda will become adsorbed, thus laying up a store of an active chemical base which will more or less rapidly become changed into other substances, with consequent disintegration of the stone surface due to pressure. Incidentally it may be mentioned that in some experiments made by the author certain stones took different periods of time to become saturated with caustic soda solution of the same strength, and several weeks elapsed before the whole of this chemical was converted into neutral salts by the action of the acid gases carried in the atmosphere. The stones used in these experiments were Portland, Ancaster, and Park Nook, and it was found that the caustic soda absorbed by Portland stone was changed the soonest, and that by the Park Nook took the longest time to become altered. In regard to the time required to become entirely saturated with the caustic soda solution, Ancaster stone came first, Park Nook second, and Portland last. The crops of crystals which formed on the surface of the stones after a similar time were largest on the Portland stone and smallest on the Park Nook.

The chemical changes which caustic soda undergoes after it has been put on to stone are the conversion into carbonate, and probably bicarbonate, of soda by the action of the carbon dioxide in the atmosphere and in rain-water, and also the formation of sodium sulphate by the action of sulphuric acid, which is also carried both in the atmosphere and in

rain. These changes in state not only produce alterations in molecular volume, but are the commencement of crystal growth, both of which, as has already been explained, cause pressure which will eventually disintegrate stone at its surface. The change in molecular volume produced when caustic soda is converted into sodium carbonate (Na_2CO_3) is represented by the ratio 1 : 1.12, but as the sodium carbonate takes unto itself 10 molecules of water of crystallization, forming $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$, the increase in molecular volume is considerable, the ratio being 1 : 5.26. In regard to the alteration in molecular volume when caustic soda is converted into sodium sulphate, there is in this case also a considerable increase, for this substance, when crystallizing from water, forms $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, which shows an increase expressed in the ratio of 1 : 5.77.

In all but one of the steam-brush or steam-cleaning processes known to the author, caustic soda is used, particularly when cleaning the limestones and some of the dolomites, and in the case of many of the limestones, and frequently that of Portland stone, the amount of this deleterious chemical which becomes absorbed into the stone texture during the "pickling" process is considerable, and as it soaks in so deeply in many cases, and especially those in which the stone is soft and highly absorbent, it becomes impossible to remove it during the latter portion of the steam-cleaning process, and therefore, as the stone dries out, crystals of sodium carbonate and also sodium sulphate form on and under the immediate surface of the stone. In London, and cities the atmospheres of which are similarly polluted, any sodium carbonate which is formed is very quickly changed into sodium sulphate.

Whilst the chief portions of stone façades which suffer from the use of caustic soda are arrises, mouldings, and enrichments, plain ashlar is frequently affected, especially if the stone is porous or in a somewhat badly decayed state before being cleaned. This, however, is not all, for the author recently came across two elevations—one in Portland

stone and the other in a Bath stone—both of which were dirty but free of decay, which after a steam-cleaning process, in which caustic soda had been used, showed signs of incipient decay a few weeks after the jobs were finished, and within three months the decay was so bad on some portions of the stone that one would have thought it had been weathering for several years in an exceedingly foul atmosphere. These are not isolated cases by any means; it is possible to mention many instances of bad decay being brought about by the use of this very dangerous chemical.

In the chapter on the preservation of stone the matter of steam cleaning is taken up somewhat fully, and it will be pointed out that it is possible to clean all types of stone by this process without injuring them, and as it is such an important matter to architects and others who are responsible for their clients' buildings to know that the corrosive chemical, caustic soda, is not employed in any form or disguise whatever in conjunction with steam, they should make strict enquiries and demand a guarantee before allowing a steam-cleaning process to be used on their work.

Soap.—Whilst soap is not deposited from the atmosphere, nor does it gain access to stone by the usual laws of nature, it is put on to stone by some who in their ignorance do not understand its constitution, physical and chemical properties, nor its action on the chemicals collectively called stone.

Speaking broadly, soaps are produced by an interaction between the glycerides¹ and caustic alkalies,² and according to the type of glyceride and alkali used, hard or soft soap results.

When soap—hard or soft—is employed for the purpose of cleaning (?) stone, it is put on in the form of a moderately weak “solution” or a thin paste, and it is sometimes mixed with inert substances such as sand or pumice powder. These latter materials do not concern the subject now under consideration. All “solutions” of soap in water react slightly

¹ Vegetable and animal oils and fats.

² Caustic soda and caustic potash.

alkaline, for when these " solutions " are prepared a portion of the soap is hydrolyzed¹ into acid soap and free alkali. The free alkali is actually caustic soda; and the action of this substance when placed on stone is dealt with on p. 201. It is quite obvious that the more " porous " or coarse-grained the stone the more difficult it will be to remove the soap and its decomposition products by a subsequent operation.

The calcium carbonate of limestones will bring about a slight decomposition of soap when the latter is in " solution," and this, in combination with the adsorption of the acid soap already in the " solution," results in a somewhat greasy surface on the stone, and furthermore, discoloration is liable to occur after a time, due chiefly to the presence of iron salts in the soap and to the oxidation of the fatty acid portion of the acid soap. Any whitish bloom on a stone, and much of the apparent clean appearance after a treatment with soap or a soap preparation, is due to the presence of sodium carbonate and/or sodium sulphate produced by the action of atmospheric impurities on the caustic soda set free from the soap.

Thin films of soap " solution," and also thin films of wet soap, can be decomposed by carbon dioxide, forming sodium carbonate as one of the products; it is necessary, of course, that sufficient carbon dioxide be present to prevent a recombination between the sodium carbonate and the fatty acid set free. Now, in an atmosphere like that of London there is not only sufficient carbon dioxide to bring about this type of decomposition, but often sufficient sulphuric acid not only to convert the sodium carbonate into sodium sulphate, but to decompose the soap films more rapidly than the carbon dioxide; more particularly is this the case during the cold months of the year.

In those processes of so-called cleaning of stone in which soap or soap preparations are used, the material is often left on the stone overnight, and should the stone get wet by

¹ For the meaning of this term see p. 184.

polluted rain or mists in the period between putting the soap on and the scrubbing process which follows later, then not only will decomposition take place fairly rapidly, but some of the products formed will soak below the surface of the treated stone, making it difficult to remove later. The cheaper and more alkaline the soap the greater the risk of subsequent damage, and other workers as well as the author have observed trouble occurring on stonework (and also brickwork) not only in regard to discoloration, but also in the production of incipient decay caused by the growth of crystals of sodium salts. There are processes in which caustic soda or caustic soda preparations are used before soap compositions are applied to the stone, and here we have cases in which the commencement of decay is accentuated by the caustic soda, and the reader is referred to p. 201 for details on this matter.

To advocate or to use preparations on stone or other building materials which at the best do not clean properly and always carry with their use the risk of bringing about decay, especially of enrichments and other, sometimes greatly treasured portions of a building, is an action which the architect and others interested in buildings should endeavour to check, not encourage.

CHAPTER VI

Never let it be forgotten that STONE IS A CHEMICAL, and also it is frequently THE LITTLE THINGS THAT MATTER.

IT has been stated by Mumby¹ that "the use of stone preservatives carries its own condemnation as showing that the stone has been employed in a situation for which its chemical and physical nature renders it unsuitable," but after a careful consideration of all that has been said in the chapter on the decay of building stones, the only conclusion which can be come to is that this stricture is unwarrantable.

The subject of the preservation of stone is of very great importance, and it is at the same time one beset with very many difficulties, the solving of which requires the united efforts of the physicist, chemist, and geologist.

Many of our historical buildings are rapidly falling into a state of decay; all their magnificent enrichments, the results of many labours of love, the materialized ideas of those whose thoughts were first and last centred on the production of the beautiful, are being lost for ever, and to do the best possible to aid in the work of preserving these valuable treasures is a duty to those who are to come after us, so that our enjoyments may be theirs, and the hand of time will not stale the effects these great works produce on the mind.

Very little headway has been made in the science of preservation of stone, and until just recently the subject has not received the attention it merits. For quite a number of years preparations or processes have been marketed, mainly under trade names, which when used have given results falling far short of those claimed of them. This cannot be wondered at when it is noted that very few seem to recognize that stones are composed of chemical substances possessing certain definite chemical and physical properties,

¹ "The Chemistry and Physics of Building Materials," p. 215.

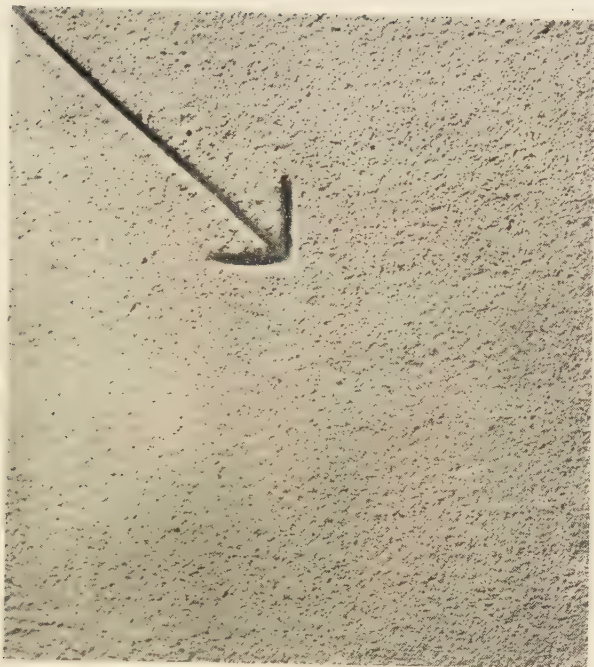


FIG. 50.—BATH STONE
Appearance of face before commencing experiments

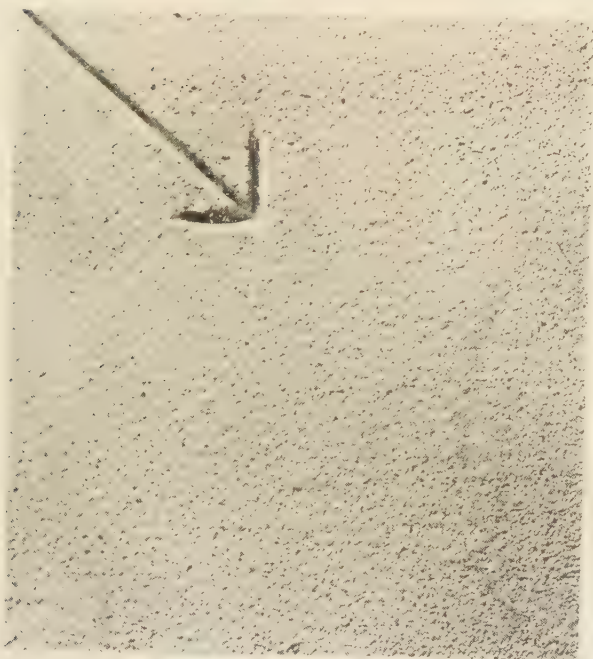


FIG. 51.—BATH STONE
Appearance of face after use of steam

and that a deep knowledge of practical and theoretical chemistry, physics, and the associated sciences, is needed to guard against injury to the stone by the use of unsuitable materials, and at the same time produce those which will give satisfactory results. Just because a substance possesses natural water-repelling properties, or can act as a kind of cement, it is not correct to claim that it is a suitable stone preservative.

If it is desired to apply a preservative treatment to the stone in a building immediately after it has been erected, then it is necessary to remove all the slurry from the face of the stone, if this material has been put on, allow the stone to *dry* thoroughly, and finally remove any dust before proceeding with the treatment. Further on in this chapter the advisability of applying preservative solutions to new stone, or leaving it untouched, will be discussed.

In regard to buildings which have been exposed to atmospheres of various degrees of pollution for a number of years, and particularly those structures in large towns and cities, the stonework will be covered for the most part with soot and grime, and the by-products of decay. On this account it will be seen that there is a need for the application of a cleaning process, not only to brighten up the building, but to allow a preservative treatment to be applied satisfactorily. To attempt to give stonework a preservative treatment whilst it is covered with dirt, etc., is the equivalent to throwing money away.

Often after an old building has been cleaned it will be found that certain portions of the plain ashlar, and also parts of the various members and enrichments, have become so decayed and softened that it is necessary to cut away the rotten material and restore in either new stone, or a stone mastic, before applying a preservative process.

Before proceeding with a description of the various materials and methods used for the preservation of stone, it is necessary to deal more or less fully with the processes of cleaning and of restoration.

The methods of cleaning stone in vogue at present may be divided into three groups—viz.:

- (1) Dry processes.
- (2) Wet processes, using water or other chemicals.
- (3) Steam-cleaning processes.

Dry Processes.—In this group may be mentioned: (*a*) working a new face; (*b*) wire brushing, and finally removing dust with softer brushes; and (*c*) superficial rubbing in the dry with carborundum or grit stones.

With reference to (*a*), this method is, or should be, carried out by masons, but it is not a process to be recommended, and unless there is some very special reason, should never be carried out, for it is expensive and usually unnecessary. It is quite true that stone worked to a new face will present a surface which is absolutely clean and which will allow preservative solutions to soak in, but the somewhat common idea that if a stone is refaced the new face produced is equal to that of a face on a new and unweathered stone is not altogether correct; it is found by experience that after a stone has been in a building for thirty or more years and subjected to all sorts of weather, the whole mass becomes somewhat softer in texture, due chiefly to the gradual washing out of the finer parts of the matrix by the continual wetting with polluted water. If the method under consideration is used it cannot be certain that all the decayed stone has been removed, for in certain sections the decay may be much deeper than in others.

In regard to (*b*), this process is one of the most unsatisfactory methods of cleaning stone. It does not produce a clean surface, but simply removes the loose soot and grime, and also the very loose and decayed portions of the stone, resulting in a condition which makes it very difficult to get good results by a preservative process. Some of the softer stones, when they are in a condition of decay, may brush up to a clean surface, but in regard to the harder and less decayed portions, this result is not realized. Enrichments

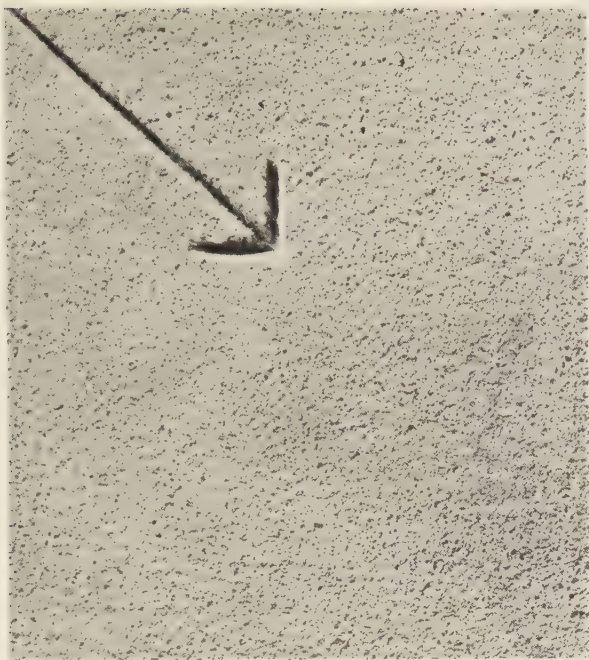


FIG. 52.—BATH STONE
Appearance of face after use of steam and a non-injurious chemical

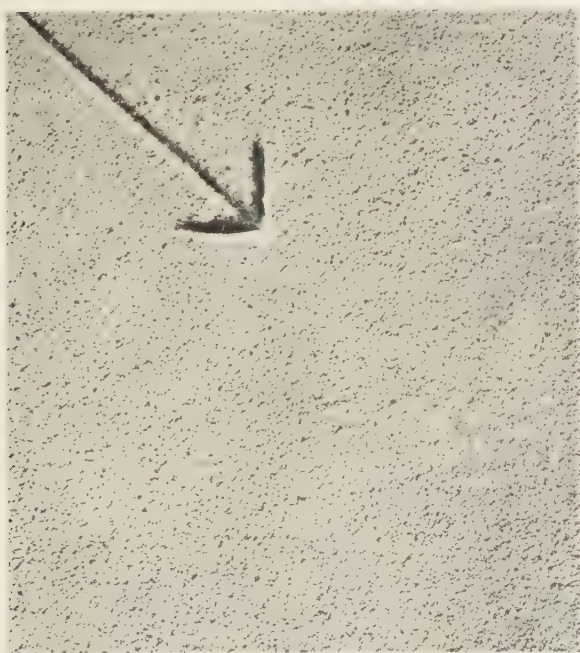


FIG. 53.—BATH STONE
Appearance of face after the use of steam, a non-injurious chemical
and a graded wire-brush

and carved work cannot be properly cleaned by the use of wire brushes, as many parts are awkwardly shaped or almost inaccessible, and very often the under portions of cornices, mouldings, beadings, stringers, etc., which have become caked up with soot and calcium sulphate cannot be cleaned at all by this process, the glass-like surface resisting all efforts towards removal.

Dealing with method (c), to attempt to clean stone properly by rubbing the dry surface with carborundum or grit stone is an absurd procedure. It is not only costly, but it is inefficient, chiefly for the reason that a large number of weathered stones which have become coated with soot and calcium sulphate incrustation present a surface of a glass-like nature which the carborundum will not grip; or, in other words, it will slip over the surface. Like the wire brush, carborundum or grit will remove the decayed portions of the stone, but there is always a tendency, especially with the coarser types of carborundum blocks, to tear the surface of the stone if used in the dry. It will be very clear to the reader that to endeavour to clean some portions of carved enrichments with carborundum is to attempt the impossible, and to risk breaking portions of the carved members.

From this brief description of the dry processes it will be noted that, with the exception of tooling or working to new face, which is an expensive and, as a rule, unnecessary process, dry methods of cleaning stone are highly unsatisfactory. The same may be said of some of the wet processes, which will be described now.

Wet Processes.—In this class may be grouped: (a) The use of clean water, hot or cold, and ordinary scrubbing brushes or “stumps”; (b) the use of soft soap or hard soap alone or mixed with or used in conjunction with pumice powder, fine sand or other grit, using water as the vehicle and scrubbing with ordinary scrubbing brushes; (c) the use of caustic soda solutions or preparations of caustic soda diluted with water; (d) the use of caustic soda or its preparations in conjunction with soap or soap and pumice powder

or other grit; (*e*) the use of caustic soda mixed with siliceous earth, pumice powder, or stone dust; (*f*) the use of hydrofluoric acid or its preparations; (*g*) the use of dilute hydrochloric acid.

In regard to (*a*), whilst cold or warm water and scrubbing brushes will remove a certain amount of superficial dirt, it is impossible to shift from the surface of dirty stone soot which has become caked on with calcium sulphate, or that which has found its way into the deep pores of many of the open-grained stones. It is also useless to attempt to clean carvings and other enrichments by this process, owing to the tenacious way in which the soot and calcium sulphate incrustation adheres to stone on the one hand, and secondly, on account of the almost, if not in many cases, impossible means of brushing round some of the members of carvings.

With reference to (*b*), in general practice it has been found that soap and water, even if employed in conjunction with pumice powder or other grit, with the use of scrubbing brushes, will not remove much more dirt and soot than clean hot water, especially in the case of open-pored stones. The detrimental effect which soaps have upon building stones has already received attention in Chapter V, p. 205, and this in itself should condemn the use of these materials even if they could satisfactorily clean stone. As methods (*c*), (*d*), and (*e*) depend primarily upon the use of caustic soda, they have been grouped together. Caustic soda solution used alone and by brushing over the stone, allowing to stand and then later scrubbing off with scrubbing brushes and water, will not remove all the dirt and grime from stonework, especially on such members as the moulded portions of main cornices and much exposed enrichments, and the same remarks can be applied to caustic soda preparations. The use of caustic soda or caustic soda preparations followed, say, some twenty-four hours afterwards by an application of carbonate of soda dissolved in water, soap and water, or soap, pumice powder, or other sort of grit and water, combined with scrubbing, will remove a good deal of



FIG. 54.—PORTLAND STONE
Appearance of face before commencing experiments

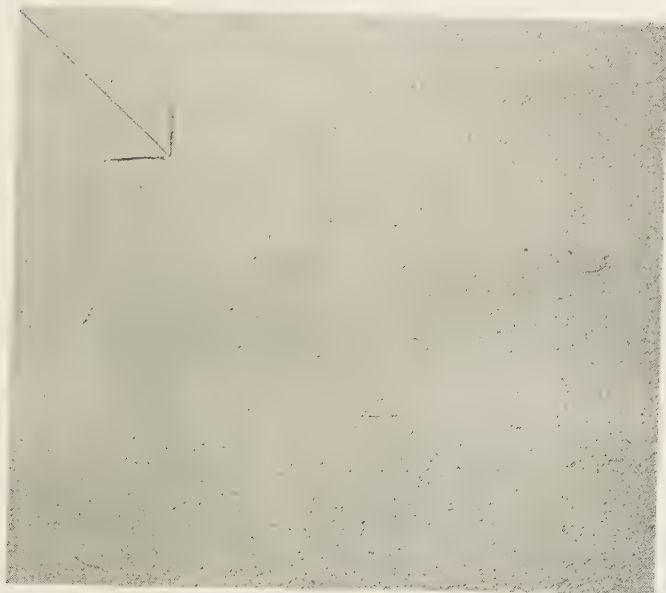


FIG. 55.—PORTLAND STONE
Appearance of face after use of steam

To face p. 212

the grime and soot from stone, but not all of it, and particularly from those members just mentioned; the same remarks can be applied to another method of scrubbing the stone with a mixture of caustic soda solution and stone dust or other type of grit. The damage produced on stones by caustic soda has already been dilated upon in Chapter V, pp. 201 to 205, and to use this material or any of its preparations, or carbonate of soda (washing soda) in the cleaning of stone is not only dangerous, but a waste of money, particularly as a good job cannot be obtained by the use of any one of them.

It is a very common practice, when any one of these wet processes has been used, to give, finally, the whole of the stonework a coating of cement wash, or a wash made up of cement and stone dust, in order to produce upon it a clean effect; *in fact, it is a method of covering up the defects of these processes*, and as a rule a dangerous one to adopt from the point of view of the weathering properties of the stone. One trouble which often arises in this connection is that crystals of sodium sulphate, produced from the chemicals used, form behind the coating of wash, and not only disintegrate this coating, but at the same time commence incipient decay on the covered surface of the stone.

In regard to (f), at times hydrofluoric acid or its preparations are used by some, particularly in cases in which it is found difficult to remove dirt stains by other of the wet chemical processes. As a rule results obtained by the use of these substances are, in the long run, highly unsatisfactory, for whilst at first there appears to be a good result, in most cases the stone treated with it ultimately becomes very much discoloured. This is due to a large extent to the presence of iron in the stone. There is another reason why this material should not be employed, and that is on account of its very highly corrosive nature and its liability to cause injury to the workmen using it unless they are careful and use goggles and rubber gloves.

Relative to (g), the author knows of cases in which hydro-

chloric acid or spirits of salt has been used with the object of cleaning stone, and he is acquainted with some in which damage has resulted. A material like this will very vigorously attack the limestones at the surface, and in a case of fine arrises, and so on, is liable to produce softening of the stone and destruction of that portion of a member. If used on sandstones, and particularly those which contain a small quantity of calcium carbonate or calcium and magnesium carbonate as a subsidiary binder, trouble is almost certain to occur at a future date, due to the partial destruction of this material owing to the action of the acid. This acid will also act more or less rapidly on the iron oxide in certain types of sandstone. If hydrochloric acid is used freely on sandstones it will soak in deeply, and if employed on interiors it will remain in the stone as free acid for a number of years.

Use of Blow-Lamp with or without Acids.—There is a method sometimes used for cleaning stone which has become very dirty, and upon which a hard surface coat has formed owing to long exposure. This is to heat the stone with a blow-lamp with or without the use of acids, the acids being applied after the stone has been heated and brushed. Hardly a more dangerous procedure could be devised, and if ever an architect or clerk-of-works sees this process being used on his building he would be well advised to prevent its continuance.

To raise the surface of a stone to high temperatures locally with a blow-lamp will not only remove hard scale from its surface by fracturing it, but it will also disintegrate the very delicate matrix, composed of calcite in the case of limestones, and of silica in the case of sandstones, thus commencing the loosening of the particles of the new surface which is exposed. To use acids in conjunction with this process, especially after the primary disintegration of the binding material by heat, is simply intensifying incipient decay.

Steam-Cleaning Processes.—The method of cleaning stone



FIG. 56.—PORTLAND STONE
Appearance of face after use of steam and a non-injurious chemical



FIG. 57.—PORTLAND STONE
Appearance of face after the use of steam, a non-injurious chemical
and a graded wire-brush

by means of jets of steam (steam brushing) is undoubtedly the most satisfactory one yet discovered, and if properly and skilfully carried out, will not produce any injury to a stone. Unfortunately it has got into ill repute owing to the fact that in conjunction with the steam, when cleaning certain classes of stone, caustic soda has been employed, the ultimate result being that much of the surface of the stone has suffered early decay owing to the growth of sodium carbonate and chiefly sodium sulphate crystals on and just underneath the surface (see p. 203). The use of caustic soda came into vogue in order to hasten the process and thus reduce its cost, but the result of this " penny wise and pound foolish " action has brought a good process into ill repute.

Steam cleaning has the advantage of enabling the user to clean mouldings, carvings, etc., with very little, if any, risk of damage. This process removes dirt and grime from a stone; *it cleans it*, but it will not always bring the surface back to its original new colour. The reason for this is the presence of somewhat deep-seated iron stains, produced by repeated soakings with polluted rain-water and the bringing forward of iron salts, which occur naturally in the stone, and depositing them on and near the surface, where they become oxidized and fixed. Nor will wet rubbing yield any better result, for the clean and new effect is due to the fine stone dust formed during the process getting into the pores of the stone like a slurry, which when dry gives the stone a whitish appearance, and covers up all stains for a time until washed out by rain.

In the steam-cleaning process, steam is generated in a vertical boiler which is placed in any convenient position on or near the building the stonework of which is to be cleaned. The steam pressure shown on the boiler gauge varies approximately between 40 and 60 pounds to the square inch, and it is probable that this fact, having come to the knowledge of those interested in the treatment of stone, has caused the formation of the idea that injury may occur to the surface, the somewhat high pressure blowing tiny pieces

out of the stone. Experiment has shown that with a boiler pressure of 60 pounds to the square inch and a length of 120 feet of $\frac{3}{4}$ -inch flexible metallic tubing, the pressure measured at the inside of the steam jet is only 14 pounds to the square inch, whilst the effective pressure exerted by the steam after it has left the nozzle of the steam brush, on a flat face, such as that of stone, is not more than $1\frac{1}{2}$ to 2 pounds per square inch. After the steam leaves the boiler it has to travel along a considerable length of $\frac{1}{2}$ to $\frac{3}{4}$ -inch flexible metallic tubing, and during its passage some of it is condensed; therefore the pressure is reduced. Its pressure is lowered still further by the friction in the tube, by being wire-drawn as it emerges from the jets, and also by expansion.

In regard to cleaning very dirty building stones, it is sometimes necessary to use chemical substances which will assist in loosening the dirt and soot prior to the application of the steam jet. These chemicals, in a scientifically worked-out steam-cleaning process, are non-injurious to the stone, and such substances as caustic soda or caustic soda preparations are avoided (see previous remarks on the action of this substance on stone, p. 201). In conjunction with steam, brushes of different sorts are employed, being graded according to the type of stone undergoing the cleaning process.

With the object of proving that steam cleaning properly conducted does not injure the surface of stones, a number of experiments were carried out, and the stones under treatment were photographed at different periods. The stones chosen for the experiments were Portland stone, Bath stone, red Mansfield, and red Hollington. In choosing these stones the object was to make observations on a comparatively hard and comparatively soft limestone, a dolomitic sandstone, and a true sandstone, all of which are representatives of the chief types of building stones, other than, of course, granite. Both the limestones are oolitic, and the Bath stone the more pronounced of the two; the red Mansfield has its sand grains bound largely by dolomite; and in the case of the red Hollington the sand grains are bound by silica.

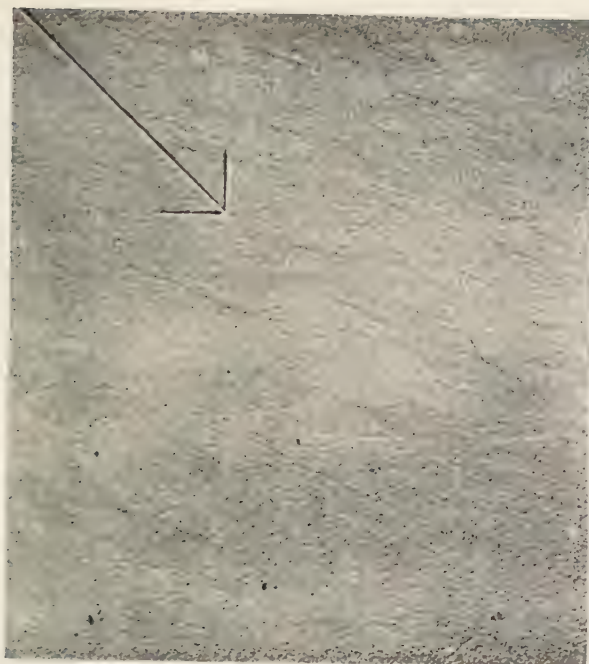


FIG. 58.—RED MANSFIELD STONE
Appearance of face before commencing experiments



FIG. 59.—RED MANSFIELD STONE
Appearance of face after use of steam

The surface of each specimen of stone experimented upon measured 2 feet by 1 foot, which gives an area of 2 square feet. This surface in each case was faced in the ordinary way by a stonemason, and then scrubbed over with a bristle scrubbing brush, using clean water, with the object of removing any fine dust which adhered to the surface and which was produced whilst the stone was being worked. The washed stones were allowed to dry, and close-up photographs then taken; the results are shown in Figs. 50, 54, 58, and 62.

Three series of experiments were then conducted upon these stones. In Series 1 the cleaned face of each stone was submitted to the action of steam as it emerged from the steam brush, without employing any other assistance, such as chemicals or fine wire brushes. The time of application of the steam was two minutes.

In Series 2 the same specimens of stone were used, but the surface was first of all treated by a chemical (not caustic soda or any of its preparations), and then allowed to remain for two minutes. After this period had elapsed the treated surface was submitted to the action of steam from the steam brush without the use of wire brushes for a further period of two minutes.

In Series 3 the previously treated stones from Series 2 were submitted to the action of steam for two minutes, using graded wire brushes according to the type of stone during the process.

After each series the stones were allowed to become dry and then close-up photographs taken.

The pressure of steam in the steam boiler throughout these experiments stood at 55 pounds to the square inch, the pressure exerted by the steam on the surface of the stone measured approximately 2 pounds to the square inch, and the temperature of the stone faces immediately after the experiments varied between 85° and 90° F.

Figs. 50, 51, 52, and 53 illustrate the effect on Bath stone. On careful examination it will be seen that the faces of the

stone throughout the series of experiments have in no way been injured. Fig. 50 illustrates the appearance of the face of the stone before the experiments were commenced, Fig. 51 after the use of steam only, Fig. 52 after the use of steam and a non-injurious chemical, Fig. 53 after the use of steam and a non-injurious chemical and a graded wire brush. Figs. 54, 55, 56, and 57 illustrate Portland stone, and these again indicate that the stone face has not been damaged; they are arranged in the same order as the Bath stones, Fig. 54 being before the experiments were commenced, and Fig. 57 after the last experiment. Figs. 58, 59, 60, and 61 show the effect on red Mansfield stone, and again it will be seen that the surface has not been injured. The last in the series is red Hollington stone (see Figs. 62, 63, 64, and 65), and upon examination it will be seen that these, like those of the other series, indicate that the surface of the stone has not in any way been damaged.

It may be contended by some readers that more definite conclusions could have been come to if decayed stone had been used in the experiments, but the author's opinion is that this could not be the case, owing to the peculiarities of and the many varied ways in which decay takes place, and the fact that in all cases of decay the depth to which it has penetrated is an inconstant factor. For instance, a piece of stone which is thickly covered with soot before cleaning could not have its face compared with that exposed after the cleaning had been completed in order to prove that the surface of the stone had been damaged or not by the process. The only way to prove whether steam cleaning does or does not injure stone is to compare the surface of a stone, the face of which can be photographed so that it clearly defines its pores and other irregularities, before and after treatment, and to carefully note at the end of the experiments whether these pores have been opened, whether ooliths have been removed, and whether the original outline of an edge has been destroyed or not.

What actually occurs when stone is steam cleaned is that

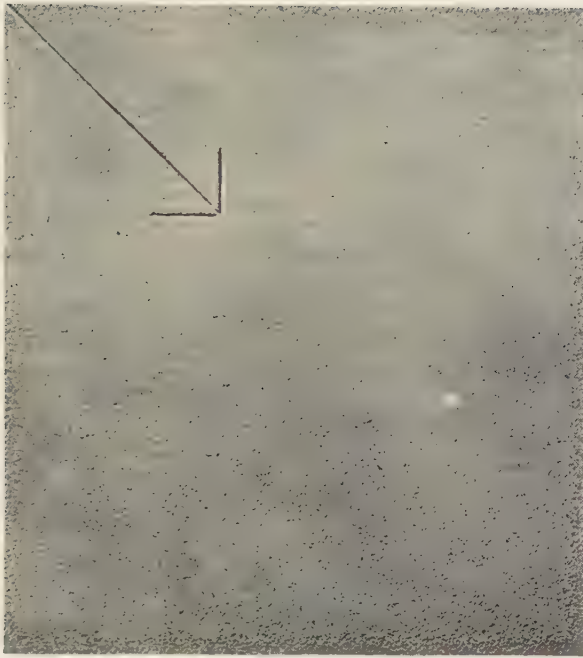


FIG. 60.—RED MANSFIELD STONE
Appearance of face after use of steam and a non-injurious chemical

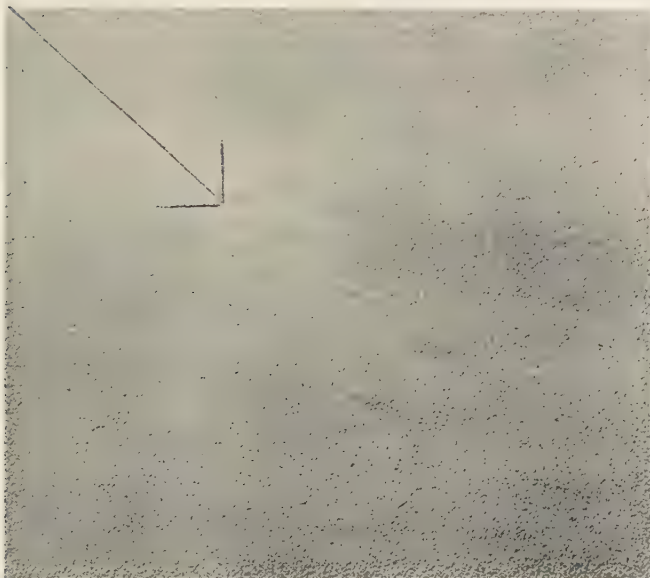


FIG. 61.—RED MANSFIELD STONE
Appearance of face after the use of steam, a non-injurious chemical and a
graded wire-brush

all the dirt and grime on the surface of the stone is softened and finally removed, and with it the already loosened and soft, decayed portions of stone, exposing in this process a cleaned surface of undecayed stone.

Although the matter of brickwork is not receiving consideration in this book, it will not be out of place to state that of the many observations made by the author upon brickwork of all kinds which has been properly steam cleaned he has seen no disturbance of the mortar joints, unless they were rotten prior to the application of the process of cleaning; neither has the face of the brickwork developed a whitish or greyish bloom after the process is finished.

CHAPTER VII

Our historical buildings are to us but sacred trusts, to watch and guard with tender care, providing at any cost protection from the devastating hand of time, so that they may be handed down to future generations to provide instruction and enjoyment to those who love the work of the old craftsmen and the monuments of history.

VERY often, after a building has been properly cleaned, those portions of the stone which have become badly decayed will require restoring either in a specially prepared mastic or by piecing with new stone. In the case of modern structures, either domestic or industrial, the restoration is usually conducted as so to conform with the original style, bringing up the restored parts to true line, all sections being reproduced, but in regard to historical buildings architects and owners differ in their opinions as to the type of restoration which should be adopted. Some prefer that the restoration be done in new stone or in stone mastic, the work to be sharp in outline and definite as to style. This may be in conformity with the original style of the old architecture, or somewhat altered but yet not out of sympathy with the original design. Others prefer the restoration to be so carried out that whilst sound in texture it appears similar to the decayed stone surrounding it, or which the restoration has replaced, still giving the building an ancient and weathered look, but at the same time putting it into a sound condition. For these reasons alone it will be clear to the reader that work of this nature should be entrusted to those who have made a thorough study of historical buildings and their styles in addition to the scientific and practical side of piecing in or restoration in mastics.

There is another type of restoration which, speaking broadly, would be more correctly described as stripping. Work of this description requires the employment of very careful workmen, possessed of more than the usual supply of patience and a love of the beauties produced by the craftsmen of the days gone by. Restoration of this nature

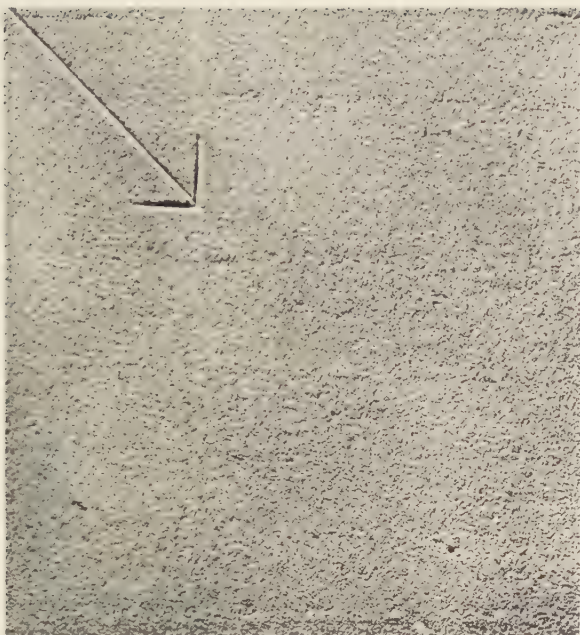


FIG. 62.—RED HOLLINGTON STONE
Appearance of face before commencing experiments

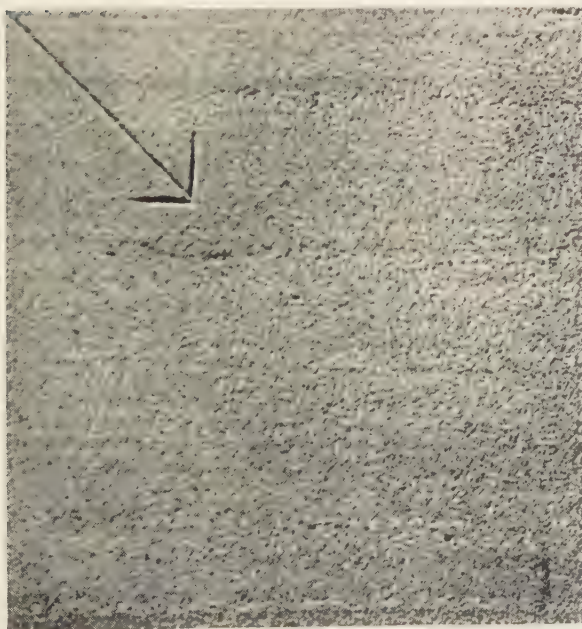


FIG. 63.—RED HOLLINGTON STONE
Appearance of face after use of steam

To face p. 220

involves the removal of one or more coats of crude plaster renderings put on by vandals to cover the surface of very fine old brickwork, wall paintings, carvings, and other beautiful enrichments. It is necessary more often than not, when this old work is exposed by the removal of the extraneous material, to give it careful attention in regard to a treatment which will protect it from the ravages of the present-day polluted atmospheres, and in no case should the preservative treatment decided upon involve the use of any substances which are of the nature of a lime or stone-wash, or a flat oil paint, for not only is the original surface hidden, but in many instances the action of decay is increased or else decay, which may be incipient, will continue to get worse whilst hidden under this artificial face, and a considerable time may elapse before it is observed, and thus irreparable damage may be caused. There is one method which is now in fashion, and that is to treat the whole work with a *lias* lime-wash. This is not only unscientific, but produces a very artificial and whitewashed effect, all out of keeping with the appearance of old and decayed masonry.

In regard to the restoration of decayed stone with various preparations known under the general appellation of metallic stone, or stone mastic, the methods adopted in preparing and using these materials are very varied and often exceedingly unscientific. Work of this nature should be, without exception, in the hands of specially trained men, and supervised by a technical man who understands not only the properties of the constituents of the materials which are used and the need for varying their compositions, but who is also acquainted, in a practical way, with the various methods of application, the importance of conforming to the general structure of the edifice upon which the preparations are used, and of the various means adopted to produce effects which make it difficult to pick out the repaired work from the surrounding original. The training possessed by the ordinary mason or plasterer is not sufficient to warrant his being employed on this class of work, also the method

so often adopted by certain people when attempting to restore or repair enrichments, mouldings, beadings, arrises, and plain ashlar, etc., with ordinary grey cement or white cement and sand mixtures, should be condemned without a second hearing if good work is desired. The chief reasons are: there is a large risk of hair cracking, which in restoration work must be avoided absolutely; true matches cannot be obtained; and there is a great liability of decay being set up at the joints between it and the cement sand mixture.

One type of composition or mastic is not suitable for the restoration of all kinds of stone; specially designed preparations should be employed on the different classes of stone, and in working out a formula due allowance must be made, as far as is humanly possible, so that the finished material, when in position on the building, will expand and contract to the same amount as that of the stone upon which it is keyed. Great care must be taken in the working of these materials to prevent hair cracking or crazing; this defect is a very common one, and is seen a great deal more than it should be in restoration in mastics. It may be stated here that a properly prepared mastic improperly used will hair crack or craze very badly; this is certainly a support to the claim that specially skilled mechanics should be employed to carry out work of this kind.

In the gauging of stone mastics the use of dangerous substances like hydrochloric or sulphuric acids, or silicate of soda, should be carefully avoided; as in the case of acids, not only are they liable to produce a weakening of the stone which comes in juxtaposition to the mastic, but they frequently badly stain the original stone. The use of acids in the gauging liquid produces a spongy or cellular structure to the mastic which in a great many instances is a source of weakness, and especially is this the case if hair cracks appear on the surface. If a solution of sulphuric acid is used for gauging and for wetting-in, the action on the original stone at the key face is one which produces calcium sulphate, a substance which causes a very considerable amount of decay

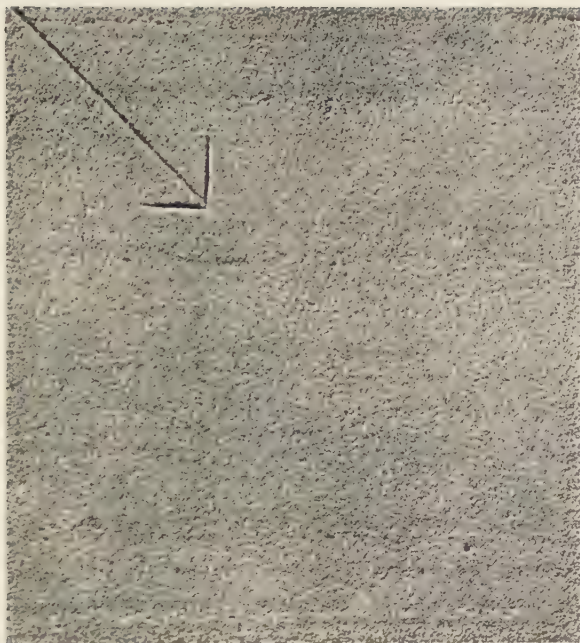


FIG. 64.—RED HOLLINGTON STONE
Appearance of face after use of steam and a non-injurious chemical

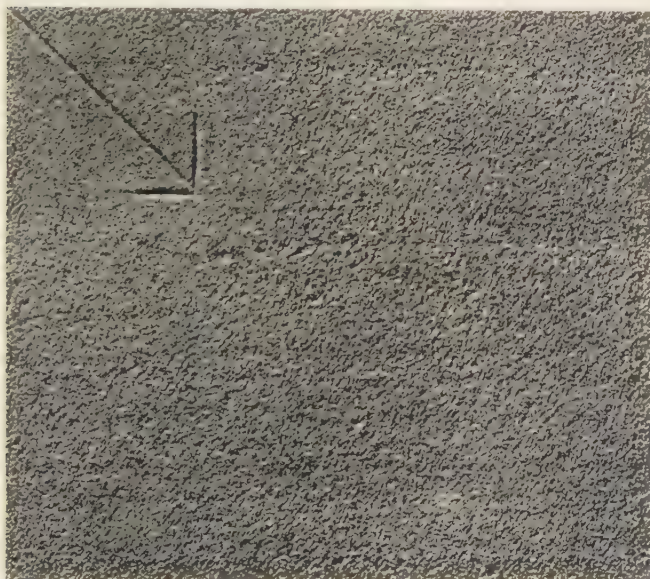


FIG. 65.—RED HOLLINGTON STONE
Appearance of face after the use of steam, a non-injurious chemical and a
graded wire-brush

in building stones. The formation of this salt behind mastic of some thickness may not affect the mastic repair, but it will if the work is thin, and it very often causes trouble in the original stone in juxtaposition to the repair portions. When silicate of soda is used, a danger exists in the formation of sodium carbonate, and finally sodium sulphate crystals in the stone close to the repaired part, which, as already pointed out, will cause surface disintegration of the original stone.

The matter of dowels and cramps is one of importance in repair work. To those who use their powers of observation it will be needless to issue a note of warning that iron dowels and cramps should never be employed. The most suitable metal to employ is copper or, better still, the new alloy "Glowray," but on special occasions it is important that dowelling or cramping be carried out by the use of non-metallic substances.

Properly designed and correctly gauged mastics will give poor or very bad results if cutting back and keying is not carried out skilfully. Too much care and careful thought on the part of the skilled mechanic who is undertaking the work cannot be given. Work of this description should be of first-class quality and well paid for, and in spite of all that is said to the contrary by modern commercialism, this method of procedure is found to be the cheapest in the end. Shallow repair work should never be permitted, even with the best types of mastic. Cutting back and keying must be varied according to the type of stone which is being repaired, and to judge the extent of its decay and how to correctly cut back and key is the special knowledge of intelligent and trained, skilled mechanics. It has been the author's duty to undertake the training of men for this type of work, and he has met with many surprises, particularly in regard to the obstinacy of certain individuals, who, whilst intelligent, cannot bring themselves into line with modern thought and practice; they will still persist in following the methods used by their fathers and grandfathers.

Under certain conditions all types of stone are amenable to repair in mastics, but unless the decayed stone is first of all examined carefully by an expert who understands properly the nature of decay, the architect or building contractor should not allow the use of mastic. Among those stones which at times will not lend themselves to repair in mastic may be mentioned red Mansfield; frequently to all outward appearances it would be possible to use a mastic on this stone, but on careful examination by an expert it will be seen that trouble would crop up within a year or two if this type of repair work was carried out; on the other hand, certain states of decay of this stone will lend themselves to this much more economical type of repairing with absolutely satisfactory results. The author has had experience of both conditions, and can speak with authority on the matter. It will be clear to the reader that it is an absurd waste of money to repair stone with mastic when it is in such a state of decay that although this material sets in a satisfactory manner it will, within a year or two, come away owing to the fact that the key face was in a state of incipient decay, and probably to some considerable depth, before the mastic was put on. Perhaps it would not be out of place here to mention that terra-cotta enrichments and also historical carvings can be very satisfactorily restored in mastics, but it is necessary to give a note of warning—viz., that they must not be of the coloured cement-sand type. Work of this nature requires special attention also in regard to matters of keying and dowelling, and should be classed among that requiring skilled specialist treatment.

Finally, let it be said that restoration in mastic should be so well done that on its completion there is no need to give the whole of the stonework a treatment with a cement-wash or a stonewash to cover up defects, say, under the pretext that it brightens up the buildings or preserves the stone.

With reference to restoration by piecing in with new stone, not only must great care be taken to cut away the old and decayed stone to a good and sound surface, but the

method of cutting back should be carried out in a fashion that will provide a satisfactory key, and wherever any great weight of stone is to be put in, or the piece used for restoration purposes is in an awkward position, dowelling should be resorted to, avoiding, of course, iron dowels, and using where possible non-metallic dowels in preference even to copper ones.

The stone used in this work must be, as far as possible, of a similar character and quality to that already existing in the structure, and if desired by the architect, so worked that it conforms with the weathered state of the balance of the stone in the structure. Joints should be as thin as possible, and for preference made in best lias lime mortar or cement mortar. Too much care cannot be taken in the choice of the mortar, especially in regard to historical buildings; a mortar containing a considerable amount of active lime is liable to produce trouble in regard to the decay of some types of stone, for when rain-water gets at it some of the lime will be leached out, carried into the stone, then to the surface, where it will sulphate and eventually crystallize, causing damage, as already described (see pp. 145 and 150).

In all types of restoration work, after the building has been put into a sound condition and all very bad parts made good, a preservative treatment to the whole surface is needed, and even to-day, in an age which may be called scientific, it cannot be said with any degree of assurance that the ideal preservative material or treatment has been discovered. It does seem illogical, however, to argue that, because an absolutely perfect preservative has not been found, decaying stone should be left untouched. Rather than allow decay to continue at a far more rapid rate to-day than in the past, it will be much better to treat stonework with as perfect a solution or process as has been discovered, submit to periodic examinations, and reprocess again after a certain period, and thus save the stone from attack. Whilst careful research may lead to the discovery of materials which, when used scientifically, will preserve stone for a

fair term of years, it will be seen later that the possibility of finding a substance or a process by the treatment of which stone will be preserved for a *very considerable* period, is very remote. Stones are chemicals and products of nature, and all known preservative substances are of similar origin directly or indirectly; they are all subject to the laws of nature, and not any one of them is indestructible. Outside these facts, a careful study of the chapter on the causes of decay will suggest other reasons why the practice of treatment, periodic inspection, and retreatment where necessary should be followed out.

To a very large extent *new* stone in a new building (sometimes new structures are built in once-used stone) does not require any drastic preservative treatment in regard to the application of solutions, with the exception, perhaps, of certain types of enrichments and those members of the façade which are liable to collect soot and dirt very rapidly, if the façade is washed down with clean water several times each year during the summer months. In the case of hard stones like Portland the plain ashlar needs only the periodic washings down, but it is wise to give the surface of the softer stones, such as those of the Bath series, one or two applications of silicon ester, provided these are applied scientifically by trained men under technical supervision, and then follow with the washing-down process during the summer-time. If it is decided to carry out this practice, then the fixing of the masonry must be well done, and the mortar and pointing of the best quality.

Unfortunately, at the present day there are more old and historical buildings undergoing serious decay, which require immediate attention and a special preservative treatment, than new buildings, which by the comparatively easy method of applying a primary protective treatment followed periodically by a process of washing down, could be kept in a good condition.

After a period of years the decay of stone in buildings becomes not only unsightly, but in very many instances

unsafe, and the need for prompt attention becomes very obvious. To restore and preserve the stonework when in this state is very often an expensive matter, and from the point of view of economy alone it is advisable to give attention to the stonework of a building long before it reaches this state.

At this stage it may be asked, Is it possible to produce a perfect or ideal stone preservative treatment or material, and what should be the properties of the material or materials used in the process? Considering all the factors concerned in the process of decay and the methods which can be used to apply a preservative treatment, the answer to the first portion of the question is, No; and the answer to the second is a very difficult one to give. Noel Heaton,¹ an earnest worker in this subject, tabulates what he considers to be the properties demanded of a perfect stone preservative; they are as under:

- (1) It must penetrate easily and deeply into the stone, and remain there on drying.
- (2) It must not concentrate on the surface so as to form a hard crust, but at the same time harden the surface sufficiently to resist erosion.
- (3) It must prevent penetration of moisture, and, at the same time, allow moisture to escape.
- (4) It must not discolour or in any way alter the natural appearance of the stone.
- (5) It must expand and contract uniformly with the stone so as not to cause flaking.
- (6) It must be non-corrosive and harmless in use.
- (7) It must be economical in material and labour of application.
- (8) It should retain its preservative effect indefinitely.

To these may be added:

- (a) It must lend itself to the treatment of stone, whether in the wet or dry condition.
- (b) It must penetrate the stone and not remain on the surface, whether it be cold or warm.

¹ "The Preservation of Stone," *Journ. Royal Soc. Arts*, December 30, 1921, p. 127.

- (c) It must not deposit any solid matter within a reasonable range of temperature.
- (d) The solid matter in the preservative must not be attacked by any acid or alkaline substances.
- (e) It must not take up the crystalline state and thus introduce the danger of surface disintegration owing to the growth of crystals.
- (f) It must not depend for its preservative properties on a reaction between the stone substance and itself.

It will be just as well, before proceeding further, to discuss these various requisites in the order given.

1. By this statement it is evidently meant that the solution of the preservative substance must penetrate the stone easily and deeply, and that on evaporation of the solvent the solid portion representing the actual preservative must remain on all those parts touched by its solution. Quite a number of solutions supplied as preservatives penetrate into stone easily, but for any one of them, or even a perfect preservative, to penetrate deeply, will require *very many applications*; in practice, if a solution is applied to a stone by means of a brush or a spraying apparatus, one application of a unit quantity (say, 1 gallon) will cover a large area (say, 50 square yards), which means that penetration is not very deep. If a perfect stone preservative were discovered, to secure deep penetration would mean a large consumption of material and a heavy labour bill; even with the best-known preservatives now obtainable the same argument applies.

In considering the requirement that the preservative substance in a solution must remain on those parts of the stone which have been "wetted" by that solution, no matter how deep it has penetrated, the following facts must not be overlooked:

- (a) Positive adsorption¹ must take place.
- (b) Adsorption must be strong enough to retain the dissolved material whilst the solvent is moving towards the exterior surface by capillary action, prior to evaporating, thus preventing a concentration of the solid on this surface when evaporation takes place.

¹ For an explanation of this phenomenon see p. 154.

- (c) The adsorbed material (the preservative) must not retain sufficient of the solvent to keep it moist or soft.
- (d) Bearing in mind that adsorption is selective, then the substance suggested as a preservative must be capable of becoming adsorbed by the particles of the stone.
- (e) That the various types of stone will exhibit differences in adsorption.

2. The first section of this demand has received some consideration under No. 1 above. If the solid concentrates on the surface as explained, then it will form a hard or soft crust, according to the nature of the preservative material. The suggestion that the preservative must harden the surface sufficiently to resist erosion must be considered carefully. Presumably what is meant is that the exterior surface of the stone must be hardened by the preservative so as to enable it to resist corrosive chemical action. Now it does not follow that a hardened surface will prevent decay. Irrespective of the fact that there are materials which will harden the surface of stone, but which at the same time are acted upon by the corrosive substances in the atmosphere, to use a material which is, for all practical purposes, chemically inert, does not necessarily mean success. For instance, a surface may be hardened by a satisfactory material, and yet be sufficiently porous to allow polluted water to pass through it. The effect of this will be a chemical attack on the stone behind the hardened surface, and ultimately decay by crumbling and exfoliation will set in. This means, then, that whilst it is an advantage to harden the surface of a stone with a chemically inert substance, to secure the best results this treated surface should be waterproofed; but in doing this the pores of the stone must not be closed.

3. With reference to this demand there are a few substances known which, if properly applied to stone, will effectively prevent the penetration of liquid water for a period of time, and at the same time allow water vapour to escape. It must be thoroughly understood here, that if the treat-

ment prevents liquid water from soaking into the stone, then it will also prevent water from coming out of the stone in the same form. If water vapour is to escape, then the treatment must not close the pores of the stone, nor form a continuous surface film. Good penetration of the solution and positive adsorption of the preservative substance are also essential to obtain satisfactory results.

4. To expect to treat the surface of new and clean stone with a preservative solution and not produce a little discoloration, or rather, a slight deepening of shade, is to anticipate a little too much. A few moments' thought given to this matter will make it very clear that all organic substances which may be useful for waterproofing stone will naturally deepen the shade a little, producing an effect more or less like that when stone is wetted with water. In regard to those inorganic substances which possess the property of hardening or consolidating decaying stone, a few do not discolour stone, but rather whiten the surface, and the one which gives the best results slightly deepens the shade. It should be noted that inorganic preparations do not waterproof stone and, therefore, moisture from the atmosphere can pass into it. All those who value the natural appearance of stone will avoid the use of those so-called stone preservatives which produce a whitewash or limewash effect when applied.

5. When considering this demand it should be borne in mind that all substances have a definite coefficient of expansion of their own, and therefore the several constituents of the different stones will vary in their rates of expansion and contraction. Flaking is not necessarily caused by a difference in expansion or contraction; it is produced more often than not by the action of crystal growth and/or change in the molecular volume of the by-products of decay, or of foreign substances introduced into the stone under the guise of preservatives.

6. To demand that a stone preservative should possess these properties is just common sense; unfortunately, many

materials have been suggested, and some used frequently, which are corrosive and harmful.

7. The amount of material used per unit of area will depend chiefly upon the type and condition of the stone which is treated by it—viz., the volume absorbed per application and the number of applications necessary. Cost of labour depends upon five chief factors: the kind of stone; its condition; whether it is in plain ashlar, moulded members, or carved enrichments; the number of applications necessary; and the means which can be employed for getting at the work. It is not possible to fix one cost figure for labour and one for material which will apply to every work, nor is it correct to specify two applications of a preservative solution for all classes and conditions of stone.

8. In regard to this statement it must be remembered that all products of nature, after manipulation by man or not, are subject to disintegration in one form or another, over varying periods of time, so all that can be hoped for is a preservative substance which will protect stone for a definite and not too short a period. The fact must not be overlooked that the life of a preservative treatment may be shortened by certain structural defects, among other things, which will allow chemical reactions to take place behind the preserved surface.

(a) In regard to this demand it should be noted that practically every type of solution offered as a preservative can be applied to stone when it is in a dry condition, but there are very few, if any at all, which can be used on wet stone with any measure of success; and the latter portion of this remark concerns particularly those solutions of an organic nature which are for the purpose of waterproofing stone.

(b) Whilst nearly all the preparations sold as stone preservatives will penetrate more or less into warm stone, the greater number will not penetrate into cold stone, and these are chiefly of the organic (waxy) type.

(c) If a preservative solution deposits all or a portion of

its solid matter at a temperature between 40° F. and 75° F., then it is quite unsuitable for the treatment of stone, as in the majority of cases the stone in buildings in this country is at a temperature within this range throughout the whole of the year.

(d) The reasons for demanding this property will be very clearly understood. It is the solid matter of a preservative solution which acts as the protective substance on and below the immediate surface of the stone, and as the impurities in the atmosphere and rain are usually of an acid nature directly or indirectly (they may at times be alkaline), then a preservative solution containing a reactive material will break down in time under these circumstances.

(e) This remark applies chiefly to inorganic preservative materials. The colloidal state (not the suspensoid state) is undoubtedly the most satisfactory one for a preservative substance to be in. In this state it is possible for it to act as a kind of glue which will assist in binding loosened particles and also strengthen the natural binding material of the stone, and at the same time form a more or less continuous covering over the stone particles. If, however, the colloidal state changes at some later period into the crystalline condition, then it will mean disintegration eventually. It has been stated by Fox and Harrison¹ that "if colloid filling² materials are used, there is the possibility that they may absorb³ gases from without, and eventually present them to the stone in a more concentrated form, thereby tending to hasten the process of decay." Whilst adsorption at the surface of a solid brings about increased concentration and a speeding-up of reaction velocity, it must be noted that in the subject under consideration the preservative material is the solid offering the surface which may adsorb the gas, and *if it is a true preservative then it must resist even a concentrated chemical attack.* Taking a limestone for the

¹ "Some Aspects of Stone Decay," *J.S.C.I.*, April 3, 1925, p. 1481.

² Why "filling" materials?

³ Surely this should be "adsorb"!

example, then the calcite of which it is composed is crystalline and not colloidal, and to argue that the preservative material which is colloidal will first bring about a concentration of an active gas on its surface, and then transfer this gas in a concentrated form to the non-colloidal calcite of the stone beneath that which has been covered with the preservative, appears to be inconsistent; and it must be remembered that when a substance becomes adsorbed on a surface it is very difficult to remove it from that surface.

In the opinion of the author there are certain colloid substances which possess great possibilities in regard to their value as stone preservatives, and the whole subject is worthy of careful investigation.

(f) It will be very clear to the reader that to disturb, even in the slightest degree, the natural binding material or the finer portions of the clastic of a stone, is to weaken somewhat the strength of the portion so acted upon. If a chemical is used which has the power of reacting with the constituents of a stone, then the original substance of that stone is changed in state, and whilst doing this some of it may be permanently or temporarily taken into solution. The seriousness of this action will be more clearly understood if a careful examination is made of micro-sections of some of the limestones. It will be seen on this examination how delicate the crystals of calcite are, and how in many cases the portions linking, say, ooliths together, is very small; only a slight chemical reaction between these slender attachments and a foreign chemical will set loose the ooliths. Now, careful experiment has shown in many cases that the foreign consolidating material which is deposited after chemical reaction does not possess the same binding powers as the natural matrix, and often a binding effect is not obtained until an excess of the reacting chemical has been added to the stone. This matter will be discussed further under the heading of silicofluorides (see p. 245).

In the study of the preservation of stone, exclusive of a broad knowledge of organic and inorganic chemistry, a

thorough acquaintance with physical chemistry is needed, and some of the most important physical phenomena associated with this subject are the types of surface energy known as surface tension and interfacial tension respectively, and also those known collectively as adsorption. To readers who are not acquainted with these phenomena the following explanations, which have been made as simple as possible, may be of assistance.

If a glass tumbler is filled with water to the brim and metal coins dropped carefully to the bottom, allowing them to fall through the centre of the column of water, it will be noticed that quite a number can be placed in the tumbler before the water runs over the edge, and if the surface of the water is examined before this occurs, it will be seen that it is curved at the edge and appears to be held in this form by an elastic skin. Actually a skin does not exist, the water being held in position by the resultant of certain molecular forces acting on the molecules near the surface. This force exerts a pressure on the interior of the liquid (in this case water) similar to that caused by an elastic skin, and it is this pressure which is called surface tension. When water or other liquids are allowed to fall through air, the spherical form is developed and the same form is seen in dewdrops on the leaves of plants. Here again it is the pressure exerted by the surface film towards the interior which produces the spherical form, and which is called surface tension. All substances, whether they be solid or liquid, exhibit surface tension at their surfaces. To imagine a film on the surface of a solid (and of the same nature as the solid) exerting a tension is not very easy, yet such a force undoubtedly exists. Now, when a drop of liquid is placed on the surface of a solid, at the point of contact (the interface) there will be the surface tension of the liquid and the surface tension of the solid, the joint action of which is known as interfacial tension. A further explanation of interfacial tension is given on p. 165.

In regard to adsorption phenomena, these are of great

variety, and the term "adsorption," used in its widest sense, covers some types of energy which are not strictly confined to the closer and more accurate understanding of this function. True adsorption concerns the concentration of dispersed colloid particles,¹ or molecular dispersoids,² a change in state which takes place at the surface of contact when the dispersion medium and a solid material are brought together. That is to say, if a liquid containing colloid particles or molecular dispersoids evenly distributed throughout it is brought into contact with a solid material, then the dispersed substance will concentrate in proximity to the surface of the solid.

Many substances have been discovered which possess the power of bringing about adsorption, and it is quite likely that all materials under certain conditions are able to exert this type of energy. As an example may be cited the fact that if bone charcoal, which possesses very powerful adsorptive properties, is added to a "solution" of a dye known as fuchsin and the mixture shaken up and allowed to settle, it will be noted that the "solution" has become colourless, all the dye having been adsorbed by the charcoal. True adsorption is a reversible process, and this means that the adsorbed substance can be removed from the adsorbing material by shaking it with the same or another solvent. Some substances, however, after they have become adsorbed, develop such a strong attachment that it is practically impossible to remove them; functions of this nature are known as pseudo-adsorption.

There is often a very strong attachment between the adsorbed substance and the adsorbing material, and an instance of this is found in the following: Gelatin in water is strongly adsorbed by glass. If a "solution" of gelatin is allowed to dry upon a glass plate, particularly at a slightly elevated temperature, as the colloid gelatin loses water it

¹ Colloid particles vary in size between 0·00004 inch and 0·00000004 inch.

² Molecular dispersoids are smaller than 0·00000004 inch.

will contract. It has, however, become so firmly attached to the glass surface by adsorption that it will actually pull off chips during the process of contraction. On the other hand, if the same experiment is tried on a plate of mica or calcite the results are in the negative.

Experiments have shown that most stones do not possess the power of adsorbing the materials which form the active principles of nearly all the waterproofing and consolidating solutions, and this means that in spite of a more or less deep penetration of the solution the ultimate result is a surface deposit of the active material, and very often the formation of a skin, which eventually causes trouble.

It is easy to be misled into thinking that a number of applications of a preparation which has brought about a fair depth of penetration has actually deposited its preservative material on all portions of the stone from the surface to the point reached. This is not the case, however. What actually happens is, that the stone becomes wetted by the solvent only, the dissolved substances in the solution being carried back to the surface again by capillary action during the evaporation of the solvent and deposited on the immediate surface of the stone. Naturally this means that the protective property of the preservative material can only make itself felt at the surface, and this is certainly a very weak factor in the matter of stone preservation.

In a large number of experiments made in America¹ in which waterproofing solutions of American make were used with the object of testing relative effectiveness, durability, and penetration, limestone slabs were prepared in the form of wedges in order to obtain thin edges. Ostensibly the object of the thin edges was for the purpose of finding out how deep the materials under test penetrated into the stones. How thin these edges were is not recorded, but it was found that not one of the preparations tested penetrated through the slab at this point. Among the conclusions come

¹ Technologic Papers of the Bureau of Standards, No. 248: D. W. Kessler.

to by Kessler are two which concern this portion of the subject, and they are: (1) that "the effectiveness of any waterproofing may be greatly influenced by the character of the pores in the stone," and (2) that "stones having close textures are more difficult to waterproof than those with large pores."

In the application of a stone preservative solution, be it of an aqueous, spirituous, or oily nature, the first and most necessary function is that the particles of the stone under treatment become properly "wetted." It is the solvent in most instances which has to "wet" the stone, and if this material functions improperly, then the dissolved matter will not be carried into the stone satisfactorily. Practically the whole function of "wetting" by a liquid depends upon interfacial tension, and for complete "wetting" to take place this must be reduced almost to zero, or in other words, the surface tension of the solid must be greater than the sum of the interfacial tension between the solid and the liquid and the surface tension of the liquid (see p. 165).

It is frequently stated that liquids with a low surface tension will "wet" a solid more readily than one with a high surface tension. This is not always the case, as the following will show. Water possesses a high surface tension and oleic acid a comparatively low one, yet a piece of *clean* glass is very easily wetted by water, but not by oleic acid. On this account the function of "wetting" should be referred to the phenomenon of interfacial tension, and not surface tension. Another important point to bear in mind is that the interfacial tension varies according to the nature of the solid and/or the liquid.

All careful investigators will agree that a process suitable for the treatment of one type of stone may prove quite unsuitable for application to another, and that it is necessary to make a practical study of all the factors which enter into this subject and evolve specific methods as flexible standards. By this latter remark is meant that although, say, decaying Portland stone in many instances can be treated by the

same process, yet in another instance it will be needful to make some modifications. The necessary kinds of processes and the modifications made thereto, when needed, are arrived at by practical experience only, and cannot be taught in textbooks.

In regard to substances which can be used on decaying stone with the object of consolidating the more or less loosened particles (to consolidate is one part of a process or treatment), the opinion of several workers and the author is that one type of consolidating material will, *if of the proper kind*, prove suitable for the treatment of most, if not all, types of stones; the method of application will, of course, vary.

To maintain stone in a waterproof condition for a number of years is not a very easy matter; much depends upon the position of the stone in the structure, its condition before treatment, and the choice of the correct material. Among the materials employed from time to time for the purpose of waterproofing stone may be mentioned: linseed oil, china wood oil, liquid paraffin, petroleum jelly, paraffin wax, mineral soaps, synthetic and natural resins, glue, animal fats, cellulose compounds, and some inorganic substances such as the silicofluorides, and due consideration will be given to all these further on in this chapter.

There are three chief difficulties in regard to the process of waterproofing stone which may be mentioned here. They are:

- (a) To avoid the complete closing of the pores of the stone.
- (b) To secure a deep penetration of the actual waterproofing substance.
- (c) To prevent the waterproofing substance from being removed by water.

Opinion is divided as to whether it is advisable to use as a preservative a substance which will close the pores of the stone. For instance, C. H. Desch¹ suggests the use of

¹ "The Preservation of Building Stone," *J.S.C.I.*, April 30, 1918, p. 118t.

silicofluorides, or "fluates," and states that "carbon dioxide is freely evolved when the acid solution is applied to the surface of the stone and the *pores are closed* by the formation of silica and insoluble fluorides," whilst Noel Heaton, in a paper¹ read before the Royal Society of Arts, mentions that stone preservatives must prevent penetration of moisture, and at the same time allow moisture to escape, which means, of course, that the pores must remain open. Fox and Harrison, so it appears, lean towards the opinion that it is wise to close the pores of the stone, for in a paper² read by them they state: "Seeing that water is the chief agent and vehicle of corrosive substances as well as the weathering agent, it might prove the most desirable course in the long run to get the stone in as dry a condition as possible, and then render it impermeable so that neither water nor gases can gain admittance." There seems very little doubt about the advantage of completely closing the pores of a stone, *if, before that is done, it is absolutely dry (not as dry as possible), and that when in position in a building it will be impossible for water to get into it by way of any of the untreated faces or via structural defects.* If, however, this proposition is considered from a practical point of view, it will be seen very easily how impossible it is to secure the necessary conditions. In this country not only the weather, but the methods used in the practice of building preclude absolutely the obtaining of a perfectly dry stone. Close the pores of a stone containing moisture and dissolved salts, and trouble will eventually occur, owing to capillary action; the pressure of water vapour and the crystallization of salts beneath the layer of material which has closed the pores will more or less speedily cause its disintegration.

To close the pores of a stone *completely* with the "fluates" is hardly possible from a practical point of view, even although used in the form of a concentrated solution and in excess, but a glassy surface can be produced on some

¹ *Journ. Royal Soc. Arts*, December 30, 1921, p. 127.

² "Some Aspects of Stone Decay," *J.S.C.I.*, April 3, 1925, p. 147T.

close-grained limestones. This glassy surface is generally slightly porous, but sufficiently close to assist decay under the surface, with consequent exfoliation. Under less concentrated conditions a precipitate of a mixture of silica and insoluble fluorides produced by double decomposition will be formed in the pores of the stone and around the small particles. This precipitate, if colloidal, will shrink a little during drying and, therefore, will not close the pores completely, and if crystalline the same result, but somewhat more marked, will be the case. In instances in which the pores are not completely closed there will still be sufficient points of ingress for polluted rain-water or corrosive gases if these happen to be carried in the atmosphere, and whilst the action of decay may be slower, it will nevertheless be sure and more liable to produce pitting and exfoliation. The author and his colleagues, after making numerous experiments in the laboratory and a very considerable number of practical observations in the field, have come to the conclusion that the wisest plan is not to completely close the pores of the stone, but to produce a condition in these pores and on the surface of the stone which will prevent moisture from passing into the stone by capillary action.

From what has already been said on p. 228, to obtain deep penetration by the use of solutions of solid substances presents a difficult proposition. On the other hand, such materials as linseed oil, boiled or raw, or china wood oil, when properly prepared, do not carry any solid matter which will eventually come back to the surface by capillary action, nor do they evaporate in order to become dry. They are, however, not altogether satisfactory as preservatives, as will be seen later.

In considering the various methods which have been suggested from time to time for the preservation of building stones, it will be convenient to divide them into two classes—viz., consolidating processes and waterproofing processes. At the outset it is as well to point out that the best results

obtained so far have been secured by the use of a consolidating process combined with a waterproofing process.

Consolidating Processes.—At the present stage of our knowledge the most suitable consolidating material for use on decaying stones is silica, and the only satisfactory way of depositing this substance is by the use of an alcoholic solution of silicon ester.¹ This substance, when exposed to air containing moisture (and the atmosphere always does) or slightly damp stone, decomposes (hydrolyzes), depositing silica, and setting free ethyl alcohol. When silicon ester is used on stone the deposited silica acts as a binding material or cement towards the loosened grains, and at the same time covers all the particles of stone at the immediate surface with a thin film of silica, and the alcohol which is set free, being highly volatile like that of the alcoholic solvent used, evaporates away, and, therefore, there is *no* injurious by-product left in the stone which would at a later date cause trouble. The advantages claimed of this material are: (1) It penetrates easily into a stone. (2) By its use a chemically inert cement is deposited. (3) It will not close the pores of a stone with solid matter, if applied by properly trained men. (4) Being chemically inert it does not attack the natural binding material of a stone. (5) It does not produce serious discoloration. (6) It toughens the portions of the stone treated by it.

Whilst this substance will give highly satisfactory results if properly applied by specially trained workmen, under scientific supervision, there is a liability of trouble arising if used by the ordinary painter, plasterer, or mason who has had no special training in the methods employed in the preservation of stone.

Potassium and Sodium Silicates.—The constitution of these substances varies within fairly wide limits, and they are alkaline in nature. Potassium silicate has not been used largely in the treatment of stone, but sodium silicate has found considerable application alone and in conjunction

¹ Dr. A. P. Laurie is responsible for this discovery.

with other materials. Sodium silicate (and also potassium silicate) decomposes when exposed to the atmosphere, and in this process a fair quantity of caustic alkali is produced; the disastrous action of this substance on stone has been considered on pp. 201 to 205. In order to reduce the amount of alkali set free, experiments were made with the object of producing a silicate of soda containing a minimum quantity of soda (sodium oxide), and recently the manufacturers of this product succeeded in producing a quality which contains approximately 4 molecules of silica (SiO_2) and 1 molecule of sodium oxide (Na_2O). The author has carried out a number of practical experiments on a large scale with this high-ratio material, and he has formed the opinion that there is sufficient caustic alkali set free not only to produce an unsightly efflorescence of sodium sulphate, but also to assist, rather than arrest, decay at the immediate surface of the stone. The silica which is deposited during the reaction certainly binds loosened particles, but unless the solution used is dilute there is considerable risk of the pores of the stone being practically closed and a glass-like surface resulting. To produce a surface of this nature, especially when combined with the great liability of the formation of crystals of "salts" underneath, is to court the risk of decay by exfoliation. It has been suggested by some that calcium silicate is produced by a reaction between sodium or potassium silicate and the calcium carbonate of a limestone, but the author is of the firm opinion that not more than a trace of this substance will be formed under the conditions existing when solutions of these silicates are applied to stone. Viewed from a scientific point of view, the use of these materials is not making for progress, owing chiefly to the risks introduced by the production of an alkaline by-product.

Sodium Silicate and Hydrochloric Acid.—This method was suggested with the object of precipitating into the stone silica (SiO_2) as a binding material, and it has been used from time to time by those who have not given the subject of

decay and preservation of stone serious thought. When hydrochloric acid (spirit of salts, or muriatic acid) is added to a solution of sodium silicate, decomposition takes place, silica is set free, and sodium chloride (common salt) is formed. The process used is to treat the stone first of all with a solution of sodium silicate and follow it up with one of hydrochloric acid, and rely upon the reaction just mentioned taking place. The liability of an excess or an insufficient quantity of hydrochloric acid being used will always exist; in the former case the excess of acid will react upon the stone and form calcium chloride, and at the same time tend to weaken the natural binding material, and in the latter case the unacted-upon silicate of soda will have to depend upon the carbonic acid and sulphur acids contained in the atmosphere to bring about its decomposition. The sodium chloride which is formed in this process will not only produce an unsightly effect, but is a source of danger in the case of many stones, owing to the pressure set up by its crystal growth and the consequent disintegration.

Sodium Silicate and Calcium Chloride.—In this process the stone is given alternate treatments of solutions of sodium silicate and calcium chloride, the object being to precipitate as a binding material silica and calcium silicate. This method possesses all the bad points of the one just dealt with, for the undesirable by-product sodium chloride is produced, and in addition to this there is the liability of the colloid calcium silicate changing its state, with the resultant formation of crystals by which it loses its binding power.

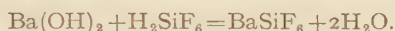
Sodium Silicate and Arsenic Acid.—This process was introduced by Hemingway, and consists in applying to the stone a weak solution of sodium silicate and then following up with a solution of arsenic acid. The reactions which take place in this process are somewhat more complicated than those just dealt with. What appears to happen is: the arsenic acid first of all reacts with the sodium silicate, forming colloidal silica and sodium arsenate. Any excess of arsenic acid will react more or less slowly with the calcium

carbonate of a limestone, if this is the type of stone receiving treatment, forming insoluble calcium arsenate and setting free carbon dioxide. Whilst calcium arsenate is insoluble in water it takes on the crystalline state and is, therefore, liable to reduce the binding powers of the precipitated colloidal silica. Sodium arsenate, on the other hand, is soluble in water, and is an undesirable by-product. When this process is used on a decayed stone a hard skin is produced on the surface, and often an unsightly appearance is given to the stone by the formation of an efflorescence. In time exfoliation of the hard surface, together with portions of stone, takes place, and this is due chiefly to the formation of crystalline substances, some of which will be sodium arsenate and calcium arsenate, behind the hard layer. In the opinion of the author this process cannot be considered as a satisfactory one for treating decayed stone.

Hydrofluosilicic Acid (H_2SiF_6).—A solution of this acid has been suggested as a stone preservative, and to a limited extent has been employed for this purpose. This substance is quite unsuitable for use on limestones, as it reacts vigorously on the calcite, producing crystalline calcium silicofluoride and setting free carbonic acid. It also discolours them, and usually produces efflorescence, or "salts," which occurs on the treated surface in patches. In regard to the sandstones, provided weather conditions are suitable, it will produce a certain amount of binding or consolidation at the surface, but to bring about this result it dissolves slowly the surface of the sand grains or the silica of the binding material, thus forming a new cement from the constituents of the stone; which makes this process unsound from the point of view of scientific stone preservation. This reaction is very slow, and, therefore, should the stone become subjected to heavy rain after application, a great deal of the acid will be washed away and the treatment rendered useless. It shows the same tendency to alter the colour of sandstones as it does that of the limestones, and the more iron these stones contain the greater the discoloration.

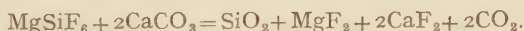
Used under the most favourable conditions without due care, it is liable to produce a hard surface which will tend to scale off eventually; it is also very uncertain in its action. The fact that it will damage the paint of window sashes and other wooden parts of a structure, and also the glazing of the windows should it fall on them, makes it an undesirable substance to use.

Hydrofluosilicic Acid and Baryta Water.—The use of these substances was suggested by Jesse Ruste, and the method adopted consists in giving the surface of a stone alternative washes of baryta water and hydrofluosilicic acid. Undoubtedly the object in this process is to precipitate into the stone barium silicofluoride, the reaction being:



Whilst barium silicofluoride is practically insoluble in water, experiment has proved that immediately it is precipitated it takes on the crystalline state, and on this account the uselessness of this method will be clearly indicated, for if crystals are precipitated on the particles of stone, then a continuous surface is not produced, and there is little or no binding effect. There is also a risk of secondary crystal growth occurring which will produce strain on the natural cement of the stone, and tend towards the production of exfoliation.

The Silicofluorides.—For a number of years the soluble silicofluorides, such as magnesium, zinc, and aluminium, have been used with the object of preserving the limestones. The reaction which takes place when magnesium silicofluoride comes in contact with calcium carbonate, say of a limestone, is as follows:



The value of the silicofluorides as stone preservatives, so it is claimed, lies in the fact that they react with calcium carbonate, as shown above, and in doing so deposit silica, magnesium fluoride, and calcium fluoride on the loosened particles of a stone, and this mixed deposit will strengthen

the natural binding material. Now, in the limestones the natural binding material, speaking generally, is calcite, occurring in the form of thin plates, and it is not to be expected that the silicofluoride will selectively react upon the oolitic portions or clastic of these stones and leave untouched the natural binding material; a chemical attack on this is quite likely to weaken its binding powers. During the reaction carbon dioxide is set free, and in the escape of this gas from the reaction surface it will disturb the deposited silica, etc., and produce a somewhat spongy effect. It is found in practice that the loosened particles of decayed stone cannot be bound together sufficiently strong by the use of the silicofluorides owing to the fact that the precipitate of consolidating substances is not sufficiently tough, and this is undoubtedly due to the fact just mentioned, and also that calcium and magnesium fluorides take on the crystalline form. It is true that a stone treated with silicofluorides appears somewhat harder than untreated stone when scratched with a penknife blade, but this does not in any way indicate that the weathering power of the stone has been increased. Whilst in some instances the use of one or a mixture of these substances appears to have given fairly good results, there are very many cases—some have been inspected by the author—in which decay has commenced after a time immediately below the surface, produced chiefly by the formation of a hard surface skin. Often the final result has been exfoliation. In certain cases, even where a hard layer has not been formed, decay has taken place, and it has been assisted largely by the growth of calcium sulphate crystals underneath the treated surface.

The use of the silicofluorides has been recommended for sandstones if these are treated first of all with a solution of a calcium salt which will react with them. Carefully considered, it will be seen that to do this is unwise, for it is liable to produce undesirable by-products, and in many cases a change in colour. Efflorescence may occur also,

being accompanied very often by disintegration of the stone at its surface.

Professor C. H. Desch¹ suggests in the use of these substances, that "should the original limestone be of very open texture, it is advisable to prepare the surface by brushing it with a cream made of dust of the same stone and water, allowing this to fill the pores before applying the silicofluoride solution. This assists in the formation of a compact layer, and does not alter the appearance of the stone." The author cannot agree with this suggestion, for in his experience he has come across quite a large number of façades of buildings which at one time or another had been brushed over with a stone dust preparation, and without exception the appearance of the original stone was very much altered. To fill the pores and form a compact layer on the surface of a stone is surely not the correct thing to do if it is desired to preserve it; practical experience shows that it is one of the best ways of increasing decay, especially by exfoliation. It has been pointed out already that the pores of a building stone should not be closed completely.

Barium Hydrate or Baryta Solution (Church's Process).—Some considerable time ago Professor Church suggested treating decaying limestones or calcareous sandstones with a solution of barium hydrate $\text{Ba}(\text{OH})_2$ with the object of converting the somewhat soluble calcium sulphate into inert and almost insoluble barium sulphate, and at the same time forming calcium hydrate, which eventually would become converted into calcium carbonate by the action of the carbon dioxide in the atmosphere. The process is now out of date, and it was proved to be a failure, one of the chief reasons being that owing to changes in molecular volume brought about by the chemical reactions just described, combined with crystal growth, exfoliation of the stone took place.

Resin Solutions.—Solutions of common resin or colophony in strengths varying between 5 and 15 per cent., made by

¹ "The Preservation of Building Stone," *J.S.C.I.*, April 30, 1918, p. 1181.

dissolving in toluol or a mixture of benzol and toluol, have been suggested and used experimentally in a fairly large way on both limestones and sandstones. The object in view in using resin was to obtain a cementing action, the resin left behind, after the evaporation of the solvents, simply sticking together or binding the loosened grains. On limestones the results were very disappointing, for the following reasons: (a) The stone was badly discoloured; (b) penetration was poor; and (c) slow chemical action between the resin acids and the calcium carbonate of the limestones gradually brought about disintegration of the cementing substance. A greater success appeared to attend the initial stages in the use of this substance on the sandstones, at any rate in regard to those stones possessing a close grain. After a time, however, it was found that disintegration of the resin cement began to take place at the surface, due to its destruction by continued wetting and also exposure to the sun's rays. Resin is one of those organic substances which, in the presence of certain light rays, undergoes what is known as autoxidation, which results in a change of state, and a powdery condition is the ultimate result.

Metallic Salts of the Fatty Acids.—Nearly eighty years ago Sylvester attempted to preserve stone by precipitating into the surface aluminium soap. This substance, a chemical combination between the metal aluminium and certain fatty acids, is insoluble in water, and when dry, tough in nature, and to a limited extent it possesses the power of forming a binding agent for the loosened particles of stone. This substance, however, will discolour stone somewhat badly as it ages, due chiefly to the trace of iron soap which it contains as an impurity. There is another very great disadvantage attached to this method, and that is the formation of potassium or sodium sulphate (according to the type of soap used) as a by-product of the reaction, and whichever of these salts is formed there is a very great liability of exfoliation occurring owing to pressure set up by crystal growth, and there is almost always a fair amount of white

efflorescence. The method of application is briefly as follows: A solution of alum is prepared by taking 1 pound of alum and dissolving it in 8 gallons of boiling water, and this solution is applied to the stone whilst hot. It is followed by a solution of Castile soap, or soft soap prepared by dissolving $\frac{3}{4}$ pound of soap in 1 gallon of boiling water. This results in a reaction between the aluminium salt and the soap which precipitates aluminium soap in the pores of the stone and around the loosened particles. Practice has shown that lasting effects do not result.

Solutions of Shellac.—The use of shellac dissolved in alcohol (methylated spirits) was suggested by the late Sir Gilbert Scott as a suitable material for consolidating decayed stone, and it appears that his method was used on some of the decayed stone in the cloisters of Westminster Abbey without success. That it was not successful cannot be wondered at if the chemical and physical properties of shellac are taken into account. Shellac contains acid bodies in varying amounts, and some commercial qualities may contain up to 20 per cent. These acids are quite capable of acting slowly upon the calcium carbonate of limestones, forming calcium salts of the acids, which will alter the stable state of the shellac film by producing crystalline or semi-crystalline substances. Another detrimental property of shellac is its power of absorbing a fair amount of water from the atmosphere. In practice the author has observed buildings the stonework of which has been treated with a shellac solution, and has noted that disintegration of the shellac film has commenced within a few months after its application. It should be mentioned, by the way, that shellac films are liable to autoxidation when exposed to the sun's rays, and owing to their brittleness are not able to withstand the attack of heavy rain or hail.

Waterproofing Processes.—Theoretically, the ideal material to use for waterproofing stone is paraffin wax; it is not acted upon by strong acids, alkalies, or oxidizing agents, at ordinary temperatures, and a few drops of water placed on a block

of this material indicate that it possesses high water-repellent properties. Laboratory tests seem to prove its great suitability for this purpose, and according to D. W. Kessler,¹ the paraffinoid bodies are the most durable and give the highest waterproofing value when used on the building stones. It should be noted that this worker's experiments were carried out on small test pieces of various stones 2 inches in diameter and $2\frac{1}{2}$ inches high, which were *thoroughly dried before the application* of the various waterproofing solutions under examination. In the opinion of the author results obtained from tests like these are not of any great practical value, because waterproofing solutions have to be used in everyday work under a variety of conditions; for instance, on stones which are *not thoroughly dry*, and on surfaces which vary in texture sometimes to quite a large extent in the same stone, and also on stone in various states of decay. Practical experience in this country with some of the paraffin wax preparations has shown failure to maintain a treated stone in a waterproofed condition for longer than three months, and the most uncertain results are obtained when this material is used on decayed stone the surface of which has been cleaned by chemicals prior to treatment, even when this stone is in as dry a condition as it is possible to secure in this country. Remarks of this sort will indicate how needful it is to insist upon specially trained and skilled workmen applying stone preservative solutions, always after an expert has examined the stone. Owing to differences in interfacial tension (wax against solid *v.* water against solid), paraffin wax will not displace a water film, and, therefore, damp stone cannot be satisfactorily waterproofed in the ordinary way by this material.

Usually paraffin wax is dissolved in a solvent such as light petroleum distillate or coal-tar naphtha, and owing to the fact that it is not highly soluble in these materials, manufacturers of proprietary compositions have been

¹ "Exposure Tests on Colourless Waterproofing Materials": Technologic Papers of the Bureau of Standards, No. 248.

tempted to add considerably more of the wax than the solvent will hold in solution at, say, between 45° and 60° F., and, therefore, at most times of the year the preparations are in a more or less "sloppy" condition. To apply a preparation in this condition to stone is simply courting disaster, for not only will it clog up the whole of the pores of the stone with wax and generally produce a semi-glossy film on the surface, but it will cause soot and grime to cling to it when it becomes softened by the heat of the sun, and in some stones it will bring about decay under the surface owing to the formation of crystals of calcium sulphate and their consequent growth. Very dilute solutions of paraffin wax are not successful in practice. Properly prepared waterproofing solutions should not contain any suspended matter at a temperature as low as 45° F., but at the same time they must not be too dilute. It stands to reason that all the suspended solid matter will be filtered out of the preparation immediately it is placed on the surface of the stone, and even if it is well scrubbed in it will only be pushed a little further into the cavities and pores, and there remain in the form of plugs, thus destroying the natural breathing properties. Paraffin wax is sometimes blended with fatty soil, such as linseed oil or china wood oil, or with a gum or resin varnish, sometimes with soft paraffin (paraffin jelly), and at times a mixture of paraffin jelly and heavy mineral oil will form the base of a waterproofing solution. The use of paraffin jelly or heavy mineral oil has not proved a success in practice; water will easily displace films of these materials. To blend paraffin wax with vegetable oils or gum resins is unscientific; it introduces reactive and somewhat unstable materials into the mixture, and there is a great risk of producing discoloration.

Vegetable Oils.—These substances have found application from time to time as waterproofers of stone, either alone or dissolved in petroleum distillate, or coal-tar naphtha. The oils usually employed are linseed, either in the raw state or after being boiled, and china wood oil, raw or specially

prepared. At times these oils are blended with rosin, prepared gums, and/or fatty acids. Linseed or china wood oil alone, and especially if dissolved in a volatile solvent, will penetrate easily and deeply into a stone, and for a time the stone will remain water-repellent. The disadvantages of using these materials are: that they discolour most stones, and that they are chemically reactive and, therefore, unstable. Boiled linseed oil or prepared china wood oil are more prone to change than the untreated oils, and their instability, so far as their use on stone is concerned, is increased by blending them with rosin, resin acids, or fatty acids. So far as arresting decay is concerned, results are uncertain. If one or two applications are given, especially on limestones, the treated stone will usually have lost its water-repellent properties within twelve to eighteen months. Some people, knowing this, have applied boiled linseed oil repeatedly until it has formed a film on the surface of the stone under treatment, and the author not so very long ago came across a building in limestone which had been treated in this fashion ten years before the inspection was made. The treated stone was almost black, and it was possible to remove a film of oxidized linseed oil, with the aid of a pen-knife, $\frac{1}{16}$ inch in thickness. In spite of this thick film the stonework showed very considerable decay, chiefly in the form of scabbing and what is known as dry-rot—that is to say, the stone was more or less decayed below the surface. The stone in the superstructure of the building was pock-marked all over owing to the covering of oxidized oil having been pushed off by the decaying stone underneath.

Colloidal Solutions or Suspensions (often incorrectly called Emulsions).—Suspensions of finely divided metallic soaps, waxes, or gum resins are offered from time to time as water-proofers of building stones. Scientifically they are wrong in principle, as they defeat the most important object in regard to the waterproofing of stone: deep penetration. The substance in suspension which constitutes the waterproofing body is not in perfect solution, but in a very fine

state of division and subject to the laws which govern colloidal suspensions, and what happens when these materials are used on stone is that the finely divided matter is precipitated (flocculated) almost immediately the suspension comes in contact with the surface. In doing this it fills up the pores of the stone in the immediate surface, and at the same time it does not form a continuous film around the particles of stone. The vehicle or dispersion phase of the suspension will penetrate into the stone, but as this is either water, light mineral oil, or turpentine, it is quite useless from the point of view of a waterproofer, and it will eventually evaporate away. In the case of the metallic soap suspensions, the finely divided particles which have been precipitated on to the immediate surface of the stone will not coalesce very rapidly, and in some cases not at all, and on this account driving rain, or, when the stone is dry, wind, will easily remove the greater part of the deposited material. The chief metallic soaps used are aluminium or calcium oleates or stearates, and these are suspended in a soap-and-water medium, or one composed of light mineral oil (white spirit), benzol, or other coal-tar distillate, and/or turpentine. Often a small quantity of vegetable oil is introduced into the preparation. Another type of colloidal solution is made up of aluminium oleate, paraffin wax, glue and water, and another consists of sodium and ammonium soaps with a small quantity of aluminium oleate, together with a dilute solution of ammonia. It should be added that gum resin varnishes, thinned down with an excess of white spirit until a suspensoid state of the gum is reached, have been offered as waterproofer of stone. Needless to say, such mixtures as these should be carefully avoided; not only will they discolour the stone, but their waterproofing and preservative properties are very limited. The soda-ammonia soap mixtures are not only useless from a practical point of view, in that the water-repellent state they produce is very limited, but they are injurious to the stone in the manner described under soaps (see p. 205).

Sundry Methods of Preserving Stone—*Marsh's Process.*—

In December, 1922, J. E. Marsh¹ published a pamphlet in which he suggested the use of caustic soda (or caustic potash) as a preservative for building stones. He contended that micro-organisms or bacteria cause decay in stones, and that a treatment with an alkali such as caustic soda would destroy these micro-organisms and render the stone sterile (see pp. 197 to 201). Marsh² also suggests adding "caustic alkali to mortars and to lime-washes so as to make them resemble, and perhaps surpass, the old mortars which preserved stone so well when lime was burned with wood instead of coal." In support of this latter suggestion he states in his pamphlet: "In the old receipt for limewash on page 5 it is to be noted that soap lees, that is to say, caustic potash or caustic soda, was one of the ingredients," and the receipt is as follows: "Collouring and splashing the north side of quardrangle and hall, $1\frac{1}{2}$ bushel of lime, 25 lb. of umber, 12 lb. of occur, 10 lb. of blue black, 6 lb. of vitrol, soap lees, beer grounds," etc. It appears that Mr. Marsh has overlooked the fact that "vitrol" (or sulphuric acid) will react with the caustic soda in the soap lees and form sodium sulphate. Judging from the way the old receipt reads, only a small quantity of soap lees was used, and therefore it could be assumed that the whole of the caustic soda would be neutralized by the sulphuric acid. Caustic potash does not occur in soap lees, and the amount of caustic soda occurring in soap lees when soap-making was a crude process could not be considered as large; there would be a fairly large quantity of common salt. It would appear, therefore, that the chances are very much against caustic alkali being present in the old limewash. A careful investigation has proved that the lime and other soluble salts in mortar contribute more or less largely to the disintegration of stone, and Dr. Laurie, the author, and others, have come

¹ "Suggestions for the Prevention of the Decay of Building Stone": Basil Blackwell, Broad Street, Oxford. 1923.

² *J.S.C.I.*, April 24, 1925, p. 427.

across numerous instances in their practice of serious decay which has been brought about by this means.

Marsh contends that a solution of 4 parts of caustic soda in 1,000 is sufficiently strong to retard the growth of micro-organisms. He gives no specific method of treatment in his pamphlet, but the following excerpt from it will enlighten the reader somewhat as to his ideas:

“ While it is true that solid caustic soda is deliquescent, a weak solution is not; and again, the deliquescence of caustic soda, if any, can hardly be more than the deliquescence of the nitrate in the decaying stone. Another objection brought against alkalies is that they may produce an unsightly efflorescence on the stone. This seems to be a direct contradiction of the other. We can hardly have it both ways. Here again the efflorescence of sodium sulphate on untreated walls seems to be one of the earliest symptoms of decay, and is more unsightly than any treatment with alkali. I have treated stone in a building with 5 and 10 per cent. solutions of caustic potash and caustic soda without any appearance either of efflorescence or of excessive wetness when the stone was clean. Where there are black lichenous patches on the stone the alkali causes a grey appearance, which can hardly be described as more unsightly than the black patches themselves.

“ The treatment I would recommend to prevent stone decay is to raise the alkalinity of the stone to something over $P_h=9$. It should not be difficult to devise a method both for testing the alkalinity of the stone in position, and for raising it to any required potential. Probably the simplest plan, however, is to increase the alkalinity of the mortar used in building, and, if necessary, in the case of large stones to fill pockets in the stone with alkaline mortar. In the case of a building under repair I would recommend the use of a similar alkaline mortar for pointing, and subsequently to wash the whole surface every five years or less with a weak solution of caustic soda.”

In regard to the statement that “ the efflorescence of

sodium sulphate on untreated walls seems to be one of the earliest symptoms of decay," the author would point out that the efflorescence which appears on *untreated stone during decay is calcium sulphate*, and that which forms after it has been treated with *caustic soda almost invariably consists of sodium sulphate*; and in a number of buildings which he has inspected, the appearance of this efflorescence of sodium sulphate is accompanied by decay, but this decay is due almost entirely to a previous use of caustic soda. He has seen buildings in Oxford which have been treated with caustic soda covered with patches of white efflorescence, and this material on analysis has proved to be sodium sulphate. This substance in one case appeared on the surface of the stone a few days after the caustic soda treatment. Investigations which are at present being carried out, coupled with the results of practical experience in the field, are convincing enough to warrant the statement: *Caustic soda should not be used either for cleaning or with the object of preserving stonework under any circumstances.*

Limewashing.—For several centuries limewash prepared in various ways was used on stone, and it is assumed that the objects were (*a*) to brighten its appearance, and (*b*) to protect it from decay. Within recent date the idea of using these preparations for the preservation of stone has been brought more or less to the fore, and it has been claimed by some that sufficient importance is not attached to the process of limewashing, and that it is an admirable and efficacious means of preserving stonework. To support this claim, attention is drawn to the fact that on examination of some of the old stonework thus treated, it was found to be in a perfect condition. The author has had the opportunity of examining quite a number of historical buildings which have been treated with limewash, and he certainly cannot agree with this contention, for whilst in some instances the stone can be considered in a fairly good condition, it is certainly not free from incipient decay, and in other instances, when the coats of lime were removed, the stone underneath

was found to be in a very bad state of decay. He does know of a case or two in which the stone has behaved exceptionally well, but on careful examination it would appear that it is rather to the peculiar properties of the stone itself, and the fact that it has not been face-bedded in places, that it has not decayed, than to its being preserved by the treatment with a limewash. Advocates of limewashing state that it is necessary to renew the treatment from time to time in order to obtain good results; in this connection the fact must not be overlooked that if an almost ideal preservative treatment were discovered this would also have to be renewed after a time, but not within anything like so short a period as with limewashing. Often when renewing the coat of lime the previous coat was not removed, and the time soon arrived when the thickness of the coats increased to such an extent that many of the finer details of enrichments, and also the tool marks where these had existed, were obliterated, and much of the beauty of the building destroyed; surely this is a most unscientific method of preserving the fine work of the old craftsmen. To limewash stone certainly introduces the risk of producing decay, as will be seen shortly.

The constitution of limewashes as made to-day varies, and the ingredients of some of them are as follows: (*a*) Fat chalk lime gauged with water containing common salt; (*b*) chalk lime gauged with boiling water and a little tallow added to the mixture; (*c*) lias lime gauged with water containing common salt and stale beer; (*d*) chalk lime gauged with water to which milk has been added; (*e*) chalk lime gauged with water containing casein.

Before lime can be used to make limewashes it has to be slaked with water, which by combination changes it from calcium oxide to calcium hydrate. This latter substance is chemically reactive, and is soluble in water to the extent of 0.17 part in 100 parts of water at 10° C. It is acted upon by the carbon dioxide in the atmosphere, especially when damp, being converted into calcium carbonate, and by

sulphuric acid and soluble sulphuric acid compounds into calcium sulphate. It should be noted that calcium carbonate is also changed into calcium sulphate by the action of these last-named substances. It has been mentioned already that calcium sulphate is soluble in water, and that it is one of the chief causes of the decay of most kinds of stone. It will be seen from these remarks that the use of limewash introduces some risk in the fact that it contains a substance, and is converted into other substances, one or all of which may injure stone under favourable conditions. It would appear from observations which have been made that this method of treatment is accompanied by greater risks if used on sandstones than on limestones. In the weathering of limewashes it is possible for a hard scale of calcium sulphate to be formed on the surface and then growth of calcium sulphate crystals to take place beneath, which will eventually push off portions of the scale with particles of stone attached. This trouble is more liable to occur if the wash is applied too thickly, or a fresh coat is applied without first of all removing the old one. The writer has seen two cases recently in which old Caen stone has been covered with a modern-made limewash prepared according to a mediæval formula, which has scaled off in places a few months after application. Now, water getting in at these places will cause trouble eventually behind those portions of limewash still remaining attached to the stone. As a matter of fact, non-continuous coats or patches of limewash will act detrimentally on some classes of stone in a similar fashion to that of the mortar joints. Limewashes made with subsidiary binding materials, like tallow or casein, are liable to form hard coverings, which, owing to their closing of the pores of the stone, will prevent free evaporation of the water contained in the stone, and which gets into it by various channels, and also cause a concentration of crystals of salts behind this hard layer which will eventually bring about disintegration of the surface of the stone, and finally exfoliation. Whilst limewashing may

have protected the walls of small structures, such as old cottages and farm buildings, which were coated every one or two years over long periods, it can hardly be said to be the case with big structures, nor would it have been possible to carry out this process economically. The use of lime-wash not only destroys the beauties of the surface of old structures—and the same may be said about it in connection with new ones—but it is uncertain in its behaviour, and on these counts alone should not be used as a preservative.

Limewashing has been recommended more or less strongly for the preservation of stone which, whilst protected from rain, is subjected to moist atmospheres, but when used under these conditions it is not always successful, and the author has seen decay taking place in the stonework in cloisters which had been limewashed only a few months before an inspection was made.

A careful consideration of all that has been written in this and the previous chapter on decay, will, it is hoped, make it clear to the reader that work in connection with restoration and preservation of stone is not simple, and should not under any circumstances be entrusted to any but those who have had a sound scientific training combined with the necessary practical experience, and all workmen employed should be specially trained. The treatment of the stonework in a building is one of great responsibility, and if not properly carried out is liable to reflect upon the architect, building contractor, or others concerned, and at the same time may cause irreparable damage, particularly if the building is historical.

Research into the causes of decay of stone and the means for its prevention must necessarily be slow. It will be accompanied by many disappointing and discouraging results, and those who take up this work must maintain an optimistic frame of mind and let their disappointments act as stimulants to further work. "Every fact and every discovery casts a light beyond itself, and the extent to which this light is perceived depends upon the man" (Gore).

INDEX

Absorption of water, 140

Abyssal rocks, 18

Acids:

arsenic, 243

carbolic, 178-179

carbonic, 172-175

hydrochloric, 177-178

hydrofluoric, 201

hydrofluosilicic, 244, 245

nitric, 178

sulphuric, 130, 131, 175-177

sulphurous, 175

Acids in atmosphere, 129, 130-132

action on stone, 171-180

Adsorption, 154, 228, 229, 232, 233, 235

Albite, 29

Algæ, 179

"Alloa granite," 19

Alum, 248, 249

Aluminium oxide, 27

Aluminium soap, 248, 249

Ammonia, 132

Ammonium chloride, 129, 131, 180-181

Ammonium sulphate, 129, 131, 153, 154, 181-182

action of, on calcite, 200

Ancaster stone, 34-38

brown weather bed, 34

chemical composition of, 36

free bed, 35

microscopical structure, 35, 36

physical properties, 36, 37

prices for fixing, 38

properties of, 34-38

red weather bed, 35

weathering of, 37

Anston stone, 38-40

chemical composition, 39

physical properties, 39

properties of, 38-40

weathering of, 39, 40

Apatite, 33

Aragonite, 24

Arenaceous rocks, 21

Arni Vein marble, 117

Arsenic acid, 243

Ashburton marble, 111, 112

Aspatria stone, 40-41

chemical composition, 40

physical properties, 41

weathering of, 41

Atmospheric pollution, 129-135

Attrition, 158

a cause of decay, 158-159

Augite, 31

Bacteria, 197-201

corrosion of stone by, 197-201

Balconies, badly designed, cause of decay, 143

Barium hydrate, 245, 247

Baryta water, 245, 247

Bath freestone, 43

Bath oolite, 41

Bath stones, 41-49

Combe Down, 43

Corsham Down, 43-44

Farleigh Down, 48

Hartham Park, 48

Monk's Park, 44-45

St. Aldhelm Box Ground, 46-47

Stoke Ground, 48-49

Beer stone, 49-50

chemical composition of, 49

physical properties of, 49

properties of, 49-50

weathering of, 50

Belgian black marble, 115

Bibliography, 33

Biologically formed rocks, 23

Biotite, 30

Blaxter stone, 50

properties of, 50

Blue Belge marble, 115

Blue Bristol Pennant stone, 52-53

chemical properties of, 53

physical properties of, 53

properties of, 52-53

weathering of, 53

Blue Forest-of-Dean stone, 67

chemical composition of, 68

microscopical examination of,

67

physical properties of, 68

price of fixing, 69

Boiled linseed oil, 240

Bolsover Moor stone, 50-51

chemical composition of, 51

physical properties of, 51

properties of, 50-51

weathering of, 51

Box Ground stone, 46-48

Bramley Fall stone, 51-52

chemical composition of, 52

physical properties of, 52

weathering of, 52

- Bricks, bad, 143-145
 cause of decay, 143-145
 Bristol Pennant stone, 93-94
 Building stones, 34-127
 acids, mineral, action on, 171-180
 ammonium chloride, action on, 180-181
 ammonium sulphate, action on, 181-182, 200
 atmospheres, polluted, their action on, 129-135
 bacteria, action on, 197-201
 CAUSTIC SODA, its action on, 201-205
 changes in temperature, the effect of, on, 159-162
 chemical salts, action on, 180-185
 consolidation of decayed, 241-249
 cracks in, 142
 crystallizing forces, their effects on, 150-158
 decay of, 128-207
 driving rain, its action on, 158
 frost, its action on, 160-169
 geology of, 1-33
 hail, action on, 158
 high temperatures, their effects on, 214
 lichens, their action on, 179-180
 linseed oil, action on, 252
 mortar, its action on, 145-148
 porosity of, 140
 preservation of, 208-259
 rain, effects on, 129, 132, 133, 134, 135, 158
 resins, their action on, 247
 rusting of iron, its effect on, 149-150
 sea water, its action on, 182-185
 shellac, action on, 249
 silicate of soda, its action on, 241-242, 243
 silicofluorides, their action on, 245
 soaps, their action on, 205-207
 soot, its action on, 129-133
 steam, its action on, 214-219
 vegetable oils, their action on, 251
 water, absorption of, 140
 water, destructive action on, 185
 waterproofing of, 249-253
 winds, effect on, 133-135
 Bunter series, 25
- Caen stone, 53-54
 chemical composition of, 54
 physical properties of, 54
 properties of, 53-54
 weathering of, 54
 Cainozoic era, 24
 Caithness stone, 54-55
 chemical composition of, 55
 physical properties of, 55
 weathering of, 54-55
 Calcite, properties of, 26
 Calcium arsenate, 244
 Calcium bicarbonate, 173
 Calcium fluoride, 245, 246
 Calcium silicate, 242, 243
 Calcium sulphate, 134, 144, 146, 147, 151, 153, 156-158, 176-177, 182, 184, 256, 258
 Campan Melange marble, 114
 Campan Rose marble, 114
 Campan Vert marble, 114
 Capillary action, 163, 165, 228
 Carbon, 131
 Carbon dioxide, 172-175
 Carbonic acid, 172-175
 Carbonic anhydride, 172-175
 Carboniferous limestone series, 25
 Carboniferous system, 25
 Caustic potash, 254
 CAUSTIC SODA, 201-205, 254-256
 Chalk stones, 59-60
 Changes in temperature, their effects on stone, 159-162
 Cheesewring granite, 119
 Chemical salts, action of, in decay, 180-185
 Chemically formed rocks, 21
 Chilmark stone, 55-56
 chemical composition of, 56
 green bed, 55
 physical properties of, 56
 pinney bed, 56
 properties of, 55-56
 trough bed, 55
 weathering of, 56
 China wood oil, 252
 Cleaning of building stones, 209-219
 dry processes, 210-211
 steam-cleaning processes, 214-219
 wet processes, 211-214
 Cleavage planes, action of, in decay, 136
 Clipsham stone, 56-58
 chemical composition of, 57
 physical properties of, 58
 price for fixing, 58
 properties of, 56-58
 weathering of, 56

- Closeburn stone, 58
 chemical composition of, 58
 physical properties of, 58
 Clunch stone, 59-60
 chemical composition of, 60
 physical properties of, 60
 weathering of, 60
 Coal Measures series, 25
 Coal gas, 131
 Coke, 131
 Colcerrow granite, 119-120
 Colloidal solutions, 252-253
 Colophony, 247
 Combe Down stone, 43
 chemical composition of, 43
 physical properties of, 43
 weathering of, 43
 Connemara marble, 113-114
 Consolidating decayed stones, 241-249
 Consolidating processes, 241-249
 Contraction, 159-162
 Correnie granite, 120
 Corsehill stone, 61-62
 chemical composition of, 62
 microscopical examination of, 62
 physical properties of, 62
 properties of, 61-62
 weathering of, 62
 Corsham Down stone, 43-44
 chemical composition of, 44
 physical properties of, 44
 weathering of, 44
 Cotswold Dale stone, 60-61
 Cracks in stone, 142
 Craigleith stone, 63
 chemical composition of, 63
 physical properties of, 63
 Cramps, causes of decay, 149-150
 Creetown granite, 120
 Cretaceous series, 24
 lower, 24
 middle, 24
 upper, 24
 Cretaceous system, 24
 Crystal growth, cause of decay, 152-158
 Crystallizing forces, their effects on stone, 150-158
 Current bedding, effects of, in decay, 136-140
 Dalbeattie granite, 121
 Damp-proof courses, 142-143
 absence of, cause of decay, 142-143
 badly made, cause of decay, 142-143
 Dancing Cairns granite, 121
 Darley Dale stone, 63-65
 chemical composition of, 64
 physical properties of, 64
 price for fixing, 65
 properties of, 63-65
 weathering of, 64
 De Lank granite, 121-122
 Decay of building stones, 128-207
 acids, action of, in, 171-180
 ammonium salts, action of, in, 180-182
 atmospheric pollution, action of, in, 129-135
 attrition, action of, in, 158-159
 bacteria, action of, in, 197-201
 bad joints (masonry), cause of, 142
 balconies, badly designed, action of, in, 143
 bricks, bad, action of, in, 143-145
 calcium sulphate, action of, in, 151, 152, 153, 156, 157, 158
 capillary action, action of, in, 163, 165, 228
 carbon dioxide, action of, in, 129, 172, 275
 casements, badly designed, cause of, 148
 CAUSTIC SODA, action of, in, 201-205, 254-256
 chemical processes in the, 128, 171-201, 201-207
 chemical salts, action of, in, 180-185
 cleavage planes, action of, in, 136
 cramps, action of, in, 149-150
 crystal growth, action of, in, 152-158
 current bedding planes, action of, in, 136-140
 damp-proof courses, defective, action of, in, 142, 143
 deoxidation, action of, in, 197
 dowels, action of, in, 149-150
 enrichments, cause of decay in, 148
 fall pipes, defective, cause of decay in, 148, 149
 frost, action of, in, 162-169
 grit, action of, in, 158-159
 hail, action of, in, 158-159
 heat, action of, in, 159-162
 hydration, action of, in, 195
 hydrochloric acid, cause of, 177-178
 iron, action of, in, 149-150

- Decay of building stones (*continued*):
 lamination planes, action of, in, 136-140
 lichens, action of, in, 170, 179-180
 magnesium sulphate, action of, in, 152, 153, 154, 156, 158
 mechanical processes in the, 128-171
 molecular volume, changes in, 150-158
 mortar, action of, in, 145-148
 natural joints, action of, in, 135-136
 nitric acid, cause of, 178
 oxidation, action of, in, 195-197
 physical processes, action of, in, 128-171
 plants, action of, in, 169-170, 179-180
 polluted atmospheres, action of, in, 133-135
 pressure, unequal, action of, in, 142
 rain, action of, in, 129, 132, 133, 134, 135, 158
 roofs, bad, cause of, 143
 "salts," action of, in, 154, 156
 settlements, action of, in, 141
 soaps, action of, in, 205, 207
 solution, part played by, in, 150, 185-195
 soot, action of, in, 129-133
 sulphuric acid, cause of, 175-177
 temperature variations, action of, in, 159-162
 weatherings, cause of, 142
 wind, action of, in, 133-135
 Deoxidation, 197
 Devonian system, 25
 Dolomite, properties of, 27
 Douling stone, 65-67
 Brambleditch, 65-66
 Chelynych, 65-66
 chemical composition of, 66
 microscopical examination of, 66
 physical properties of, 66
 weathering of, 66, 67
 Dowels, 149
 cause of decay, 149-150
 Dry processes for cleaning building stones, 210-211
 Dyce granite, 122
 Earth's crust, composition of, 20
 Emperor's red marble, 116
 Enrichments, causes of decay, 148
 Expansion of stone, 159-162
 Expansion coefficient of stone, 161
 Fall pipes, defective, cause of decay, 148-149
 False bedding, 137
 Farleigh Down stone, 48
 physical properties of, 48
 weathering of, 48
 Fatty or vegetable oils, 251
 Fatty acids, metallic salts of, 248, 253
 Felspar, properties of, 29-30
 Ferric oxide, properties of, 27-28
 Ferrous carbonate, properties of, 28
 Fissures in stone, 135
 Forest-of-Dean stones, 67-69
 blue, 67
 chemical composition of, 68
 grey, 68
 microscopical examination of, 67
 physical properties of, 68
 price of fixing, 69
 Free carbon, 131
 Frost, its action in decay, 162-169
 Garnet, properties of, 31-32
 Gattou stone, 69-70
 weathering of, 70
 Geology of building stones, 1-33
 Gifnock Liver Rock stone, 70-71
 chemical composition of, 70
 physical properties of, 70
 weathering of, 70
 Glauconite, properties of, 28, 83
 Glue, 253
 Granites, expansion of, 161
 geological age of, 26
 Granites, 119-127
 Cheesewring, 119
 Colcerrow, 119-120
 Correnie, 120
 Creetown, 120
 Dalbeattie, 121
 Dancing Cairns, 121
 De Lank, 121-122
 Dyce, 122
 Kemnay, 122
 Lamorna, 122-123
 Mountsorrel, 123
 Penryn, 123-124
 Peterhead, 124
 Princetown, 124
 Ross-of-Mull, 125
 Rubislaw, 125
 Schlattie, 126
 Shap, 126-127
 Tor, 127
 Tyrebeggar, 127
 Greek Cipollino marble, 117
 Grey Forest-of-Dean stone, 67-69

- Hæmatite, 28
 Hailes stones, 71-72
 blue, 71
 chemical composition of, 71-72
 physical properties of, 71-72
 pink, 72
 weathering of, 72
 white, 71
 Ham Hill stone, 72-75
 brown bed, 75
 grey bed, 74
 chemical composition of, 74
 physical properties of, 74
 weathering of, 75
 yellow bed, 73
 Hand-worked stone, weathering of, 170-171
 Hartham Park stone, 48
 physical properties of, 48
 weathering of, 48
 Headington stone, 75-76
 High temperatures, their effects on stone, 214
 Hollington stones, 76-79
 chemical composition of, 78
 microscopical examination of, 77
 mottled, 77
 physical properties of, 78
 price for fixing, 79
 red, 77
 white, 77
 Hopton Wood marble, 109, 112
 Hopton Wood stone, 79-80
 chemical composition of, 80
 microscopical examination of, 80
 physical properties of, 80
 weathering of, 80
 Hornblende, properties of, 30, 31
 Howley Park stone, 80
 physical properties of, 81
 Huddleston stone, 81-82
 chemical composition of, 81
 physical properties of, 81
 weathering of, 82
 Hydration in regard to decay, 195
 Hydrochloric acid, 177-178
 Hydrofluoric acid, 201
 Hydrofluosilicic acid, 244-245
 Hypabyssal rocks, 18, 19
 Igneous rocks, 18-20
 Ilmenite, properties of, 32
 Insoluble soaps, 248, 253
 Interfacial tension, 129, 165, 234
 Iona marble, 113
 Ionization, 186
 Ipplepen marble, 112
 Irish green marble, 113, 114
 Irish black marble, 113, 114
 Iron cramps, cause of, decay, 149, 150
 Iron dowels, cause of, decay, 149, 150
 Iron oxides, 27
 Iron rust, its action on stone, 149-150
 Jaune Lamartine marble, 114
 Joints, mortar, action of, in decay, 142, 145-148
 Joints, open, action of, in decay, 142
 Jurassic system, 24-25
 Kemnay granite, 122
 Kentish rag, 83-84
 chemical composition of, 84
 microscopical examination of, 84
 physical properties of, 84
 weathering of, 84
 Kenton stone, 82
 chemical composition of, 82
 physical properties of, 82
 weathering of, 82
 Ketton stone, 84-87
 chemical composition of, 86
 microscopical examination of, 85
 physical properties of, 86
 weathering of, 86
 Ketton rag, 85, 87
 Keuper series, 25
 Lamination planes, action of, in decay, 136-140
 Lamorna granite, 122-123
 Languedoc marble, 114
 Leckhampton stone, 87-88
 chemical composition of, 88
 microscopical examination of, 87
 physical properties of, 88
 weathering of, 87
 Lias series, 25
 Lichens, action on stone, 170, 179-180
 Limestones, 22, 24
 dolomitic, 23
 magnesian, 23
 oolitic, 23, 24
 Limestones:
 Ancaster, 34-38
 Anston, 38-40

Limestones (*continued*):

- Bath stones, 41-49
 - Combe Down, 43
 - Corsham Down, 43-44
 - Monk's Park, 44-46
 - St. Aldhelm Box Ground, 46-48
 - Farleigh Down, 48
 - Hartham Park, 48
 - Stoke Ground, 48-49
- Beer, 49-50
- Bolsover Moor, 50-51
- Caen, 53-54
- Chilmark, 55-56
- Clipsham, 56-58
- Clunch, 59-60
- Cotswold Dale, 60-61
- Doulting, 65-67
- Gatton, 69-70
- Ham Hill, 72-75
- Headington, 75-76
- Hopton Wood, 79-80
- Huddlestons, 81-82
- Kentish Rag, 83-84
- Ketton, 84-87
- Ketton Rag, 85-87
- Leckhampton, 87-88
- Mansfield Woodhouse, 88-89
- Minchinhampton, 91
- Nailsworth, 92
- Painswick, 92
- Park Nook, 92-93
- Portland, 94-99
- Purbeck, 100
- Roche Abbey, 103-104
- Totternhoe, 59-60
- Tadcaster, 153-154
- Weldon, 107-109
- Limewashing, 256-259
- Limonite, 28
- Lower Cretaceous series, 24
- Lower Oolite series, 25
- Lower Permian series, 25
- Machine-worked stone, weathering of, 170-171
- Magnesian limestones, 23
 - weathering of, 153
- Magnesium carbonate, properties of, 26-27
- Magnesium fluoride, 245
- Magnesium silicofluoride, 245
- Magnesium sulphate, 151, 152, 153
- Magnetite, 27
- Mansfield stones, 89-91
 - chemical composition of, 90
 - microscopical examination of, 89, 90
 - physical properties of, 90

Mansfield stones (*continued*):

- red, 89, 90
 - weathering of, 90, 91
 - white, 89, 90
- Mansfield Woodhouse, 88, 89
 - chemical composition of, 88
 - physical properties of, 89
 - weathering of, 89
- Marbles, 109-118
 - decay of, 110
 - expansion of, 110, 111, 161
 - properties of, 109, 110
 - weathering of, 110
- Marbles:
 - Arni Vein, 117
 - Ashburton, 111-112
 - Belgian Black, 115
 - Blue Belge, 115
 - Campan Melange, 114
 - Campan Rose, 114
 - Campan Vert, 114
 - Connemara Green, 113-114
 - Emperor's Red, 116
 - Greek Cipollino, 117
 - Griotte, 115
 - Hopton Wood, 112
 - Iona, 113
 - Ippepen, 112
 - Irish Black, 113
 - Irish Green, 113
 - Jaune Lamartine, 114
 - Languedoc, 114
 - Norwegian, 116-117
 - Ogwell, 112
 - Petitor, 113
 - Purbeck, 112
 - Rhondana, 118
 - Rouge Byzantine, 116
 - Rouge Griotte, 115
 - Rouge Imperial, 115
 - Rouge Royal, 115
 - St. Anne, 114
 - Statuary, 118
 - Swedish Green, 117
 - Swiss Cipollino, 117
 - Tinos, 117
 - Verde di Genova, 118
 - Vidraco, 116
- Marsh's process, 254-256
- Mechanical action of rain, 158, 159
- Mechanically formed rocks, 21
- Mesozoic era, 24, 25
- Metallic salts of fatty acids, 248, 253
- Metamorphic rocks, 18, 109
- Mica, properties of, 30
- Middle Cretaceous series, 24
- Middle Oolite series, 24
- Middle Permian series, 25
- Millstone Grit, 25

- Millstone Grit series, 25
- Minchinhampton stone, 91
 - weathering of, 91
- Minerals in rocks, 26-33
- Mode of origin of rocks, 18
 - igneous, 18-20
 - metamorphic, 18, 109
 - sedimentary, 20
- Molecular volume, changes in, cause of decay, 150-158
- Monk's Park stone, 44, 46
 - chemical composition of, 45
 - microscopical examination of, 45
 - physical properties of, 46
 - price for fixing, 46
 - weathering of, 46
- Mortar joints, action of, in decay, 142, 145-148
- Mortars, action of, in decay, 145-148
- Mountsorrel granite, 123
- Muscovite, 30
- Nailsworth stone, properties of, 92
- Natural joints, 135-136
 - assistance given to decay, 135, 136
- Nitric acid, 178
- Norwegian marbles, 116-117
- Ogwell marble, 112
- Old Red Sandstone series, 25
- Oligoclase, 29
- Ooliths, 24, 35, 42, 47, 85, 96
- Oolitic limestones, 23, 24
- Oolitic series, 24
 - lower, 25
 - middle, 24
 - upper, 24
- Organically formed rocks, 22, 23
- Orthoclase, properties of, 29
- "Overburden," 155
- Oxidation in regard to decay, 195-197
- Oxides of iron, 27
- Painswick stone, 92
- Palæozoic era, 25
- Paraffin wax, 249, 251, 253
- Park Nook stone, 92-93
 - chemical composition of, 93
 - physical properties of, 93
 - weathering of, 93
- Park Spring stone, 92
- Penetration, depth of, 166, 167
- Pennant stone, 93-94
 - chemical composition of, 93
 - physical properties of, 94
- Penryn granite, 123, 124
- Permian series, 25
 - lower, 25
 - middle, 25
 - upper, 25
- Permian system, 25
- Peterhead granite, 124
- Petitor marble, 113
- Phenolic bodies, 178, 179
- Phenols, 131, 178, 179
- Plants, cause of decay, 169-170, 179-180
- Plutonic rocks, 18, 19
- Polluted atmospheres, 129-135
- Porosity of stones, 140
- Portland stone, 94-99
 - basebed, 95
 - chemical composition of, 97
 - microscopical examination of, 96
 - physical properties of, 97
 - price of fixing, 99
 - roach, 94
 - weathering of, 97-98
 - whitbed, 94-95
- Potassium silicate, 241
- Preservation of building stones, 208-259
- Preservatives, stone, 225-259
- Pressure due to faulty design, a cause of decay, 142
- Pressure produced by the freezing of water, 162-169
- Princetown granite, 124, 125
- Prudham stone, 99
 - chemical composition of, 99
 - physical properties of, 99
 - weathering of, 99
- Purbeck marble, 112
- Purbeck stone, properties of, 100
- Quarry sap, 155
- Quarry water, 155
- Quartz, properties of, 29
- Querella stone, 100-102
 - chemical composition of, 101
 - green bed, 101
 - physical properties of, 101
 - weathering of, 101-102
 - white bed, 101
- Rain, its action on stone, 129, 132, 133, 134, 135, 158
- Rainfall, 152
- Raw linseed oil, 251
- Red Wilderness stone, 102
 - chemical composition of, 102
 - physical properties of, 102
 - weathering of, 102
- Resin solutions, 247

- Resins, 247
- Restoration of buildings, 220-225
by mastics, 221-224
by piecing in, 224-225
- Rhætic series, 25
- Rhondona marble, 105
- Robin Hood stone, 102-103
chemical composition of, 103
physical properties of, 103
- Roche Abbey stone, 103, 104
chemical composition of, 104
physical properties of, 104
weathering of, 104
- Rocks:
abyssal, 18
arenaceous, 21
biologically formed, 23
chemically formed, 23
hypabyssal, 18
igneous, 18, 20
mechanically formed, 21
metamorphic, 18, 109
mode of origin, 18
organically formed, 22, 23
plutonic, 18, 19
sedimentary, 20, 139
structural characters of, 18
volcanic, 18, 19
- Roofs, badly designed, etc., causes
of decay, 143
- Ross-of-Mull granite, 125
- Rouge Byzantine marble, 116
- Rouge Griotte marble, 115
- Rouge Imperial marble, 115
- Rouge Royal marble, 115
- Rubislaw granite, 125-126
microscopical examination of, 126
- Rusting of iron, action on building
stones, 149-150
- Rutile, 31
- St. Aldhelm Box Ground stone, 46-48
chemical composition of, 47
microscopical examination of, 47
physical properties of, 47
price for fixing, 48
weathering of, 47
- St. Anne marble, 114
- St. Bees stones, 104-106
chemical composition of, 105
head freestone, 105
microscopical examination of, 104
physical properties of, 106
red freestone, 105
- "Salts," 154-156
- Sand grains, shape of, 21
- Sandstones:
Aspatia, 40-41
Blaxter, 50
Blue Bristol Pennant, 52-53
Bramley Fall, 51
Caithness, 54-55
Closeburn, 58
Corsehill, 61
Craigleith, 63
Darley Dale, 63-65
Forest-of-Dean, 67-69
Gifnock Liver Rock, 70-71
Hailes, 71-72
Hollington, 72-79
Howley Park, 80-81
Kenton, 82
Mansfield, 89-91
Park Spring, 92-93
Pennant, 93-94
Prudham, 99
Querella, 100-102
Red Wilderness, 102
Robin Hood, 102-103
St. Bees, 104-106
Storeton, 106
Wealden, 106-107
- Sandstones, expansion of, 161
- Scattie granite, 126
- Sea water, its effect on stone, 182-185
- Secondary era, 24
- Sedimentary rocks, 18, 19, 20, 139
- Settlements, cause of decay, 141
- Shap granite, 126-127
microscopical examination of, 127
- Shellac, 249
- Shotover limestone, 75
- Silicofluorides, 201, 239, 245-247
- Silicon Ester, 241
- Soaps, action on stone, 205-207
- Sodium chloride, 182
- Sodium silicate, 241, 242, 243
- Soft soap, 205
- Soil, "salts" from, 156
- Solution, in regard to decay, 150, 185-195
- Solution pressure, 185
- Soot, 129-133
action of, on stone, 129-133
constituents of, 131
- Sphene, 32
- Statuary marbles, 118
- Steam-cleaning process, 214-219
- Stoke Ground stone, 48-49
physical properties of, 49
weathering of, 48
- Stone preservation, 208-259

- Stone preservatives, 225-259
 - properties of, perfect, 227-228
- Stones:
 - hand-worked, decay of, 170-171
 - machine-worked, decay of, 170-171
- Storeton stone, 106
 - chemical composition of, 106
 - physical properties of, 106
- Structural character of rocks, 18
- Sulphur dioxide, 129, 131, 175
- Sulphuric acid, 130, 131, 175-177
- Sulphurous acid, 175
- Surface tension, 129, 234
- Swedish Green marble, 117
- Swiss Cipollino, 117
- Tadcaster stone, 153-154
 - weathering of, 153-154
- Tarry particles in atmosphere, 130
- Temperature, variations in, 159-162
 - causes of decay, 159-162
- Tertiary era, 24
- Tinos marble, 117
- Tor granite, 127
- Totternhoe stone, 59-60
 - chemical composition of, 60
 - physical properties of, 60
 - weathering of, 60
- Tourmaline, properties of, 32
- Travertine, 23
- Triassic system, 25
- Tufas, 23
- Tyrebeggar granite, 127
- Upper Cretaceous series, 24
- Upper Devonian series, 25
- Upper Oolite series, 24
- Upper Permian series, 25
- Vegetable oils, 251
- Verde di Genova marble, 118
- Vidraco marble, 116
- Volcanic rocks, 18-19
- Water, a destructive agent to stone, 185
- Water, quarry, 155
- Waterproofing processes, 249-253
- Waterproofing stone, 249-253
- Waxes, 249-251, 253
- Wealden stone, 106-107
 - physical properties of, 107
 - weathering of, 107
- Weatherings, badly made, cause of decay, 142
- Weldon stone, 107-108
 - chemical composition of, 108
 - physical properties of, 108
- Wet processes for cleaning stone, 211-214
- Wind, action of, in decay of stone, 133, 135
- Wind-blown grit, cause of decay, 158-159
- Zinc silicofluoride, 245
- Zircon, properties of, 31

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